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Cities and Growth: The Left Brain of North American Cities: Scientists and Engineers and Urban Growth

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Abstract

This paper examines the growth of human capital in Canadian and U.S. cities. Using pooled Census of Population data for 242 urban centres, we evaluate the link between long-run employment growth and the supply of different types of skilled labour. The paper also examines whether the scientific capabilities of cities are influenced by amenities such as the size of the local cultural sector.

The first part of the paper investigates the contribution of broad and specialized forms of human capital to long-run employment growth. We differentiate between employed degree holders (a general measure of human capital) and degree holders employed in science and cultural occupations (specific measures of human capital). Our growth models investigate long-run changes in urban employment from 1980 to 2000, and control for other factors that have been posited to influence the growth of cities. These include measures of amenities that capture differences in the attractiveness of urban areas.

The second part of the paper focuses specifically on a particular type of human capital—degree holders in science and engineering occupations. Our models evaluate the factors associated with the medium- and long-run growth of these occupations. Particular attention is placed on disentangling the relationships between science and engineering growth and other forms of human capital.

Keywords: urban growth, human capital, scientists and engineers, urban amenities

Executive summary

The contribution of human capital to the growth of cities has received much attention in the urban economics and regional science literature. Explanations of urban growth now often focus as much on the skill endowments of different locations as they do on more traditional factors, such as the presence of agglomeration or localization economies. This paper uses Census of Population data on 242 Canadian and U.S. cities to investigate the relationship between human capital and urban growth. It distinguishes between broad and specialized forms of human capital, ranging from all employed degree holders to those employed in science and engineering occupations and culture occupations.

The paper suggests that the contribution of human capital to growth may rest on the underlying complementarities that result from diverse mixtures of human capital. Scientists and engineers matter most for growth when combined with a large and diverse pool of skilled workers. Our urban growth model reveals positive interactions between science and engineering employment and a larger cross-section of employed degree holders located in cities. And this latter group may be the primary mechanism through which scientists and engineers contribute to the growth process.

The analysis also suggests that amenities play a central role in shaping urban dynamics. A broad-based measure of urban amenities is positively associated with the variation in long-run employment growth across cities. Growth in cities is related both to quality of life and human capital.

Differences in urban competitiveness have been linked to the ability of cities to produce and attract highly specialized workers, such as scientists and engineers. The second part of the paper investigates the factors that underlie the growth of an urban economy’s science and engineering workforce. The analysis finds a clear relationship between these specialized workers and the broader pool of human capital located in cities. Cities with large concentrations of degree holders in non-science, non-culture occupations experience more robust science and engineering (S&E) growth than others, after controlling for a range of urban characteristics. These educated populations grow together, and there is some evidence that stronger growth in this broader class of degree holders in the 1980s led to an acceleration of private sector S&E growth in the 1990s. There is less evidence, on balance, that differences in urban amenities related to the size of the culture sector or to climate serve as important drivers of science and engineering growth.

1. Introduction

The contribution of human capital to the growth of cities has received much attention in the urban economics and regional science literature. Relatively recent research by Glaeser (1994), Glaeser, Sheinkmen and Sheifer (1995), Glaeser and Saiz (2003), and Shapiro (2005) have advanced the view that the competitive fortunes of cities are closely linked to skills and competencies of their residents. Explanations of urban growth now often focus as much on the skill endowments of different locations as they do on more traditional determinants, such as the presence of agglomeration or localization economies.

These findings have served as a starting point for much of Richard Florida's recent work (2002a and 2002b). Florida argues that specific types of skills, embodied in a group of workers he labels the 'creative class,' play a particularly important role in driving urban growth. This creative class encompasses a range of occupations that are closely linked to the innovation process, be they highly technical left-brain occupations (e.g., science and engineering occupations) or more artistic right-brain occupations (e.g., arts and design occupations).

Florida argues further that this emerging new class of worker is distinguished not only by its skills but also by its tastes. These workers are attracted to places that have a culture that is open to a wide spectrum of lifestyles. The obvious implication is that cities that possess this right mix of characteristics will be better able to attract 'creative class' workers and, in the long run, will experience higher rates of population or employment growth.

Florida's work has generated great interest in the research and policy community. This interest stems, at least in part, from the fact that Florida has been able to articulate what many consciously or unconsciously have begun to feel: that there has been a transformation of the work force toward workers with higher skill levels, and those cities that are better able to attract these kinds of workers may end up the winners in this new age. Florida attempts to tells us who these workers are and what this means for where they want to live.

In this paper, we address two related themes that underlie the urban growth literature: (1) the role of workers that have made large investments in their human capital through education (degree holders) as a driver of urban growth; and (2) the identification of factors that lead these workers to concentrate in particular cities. As we have noted above, a highly educated population has been shown to be associated with stronger urban growth. In this paper, we extend this literature, like Florida, by looking at the effect of types of highly educated workers on employment growth. In particular, we are interested in the role of scientists and engineers as drivers of urban growth, since these workers, by definition, are employed to generate, transmit and implement new ideas. We also extend the literature by asking whether it is not only the level of highly educated workers that matters, but their mix as well. If scientists and engineers are the progenitors of new products and production processes, then their effectiveness might also be influenced by their interaction with other skilled workers, be they professional managers, designers or artists, that might also play a role in the development of new products and their eventual commercialization.

If scientists and engineers are important drivers of growth, then understanding the factors that influence their relative rates of growth across cities is also important. Here we draw on Florida to understand what factors might make some cities more attractive for scientists and engineers than others, and we extend Florida's work by applying econometric techniques that attempt to account for missing variable and simultaneity bias.

To address these questions, we use comprehensive Census of Population data on 242 Canadian and U.S. cities (26 Canadian and 216 U.S.) to evaluate, first, a range of urban characteristics that have been posited to determine growth performance, and second, the factors that underlie a specialized component of this growth process—the evolution of an urban economy's science and engineering (S&E) base.

The organization of the paper is as follows. Chapter 2 describes recent studies on the relationship between urban growth and human capital that motivate our analysis. Emphasis is placed on the concepts and methods that are used to evaluate the importance of various forms of human capital.

Our analysis of urban growth is found in Chapter 3. We present bivariate tabulations on the relationship between growth, human capital and urban amenities. We then estimate a series of urban growth models that evaluate the link between long-run employment growth and different measures of human capital. Several of these models test for interaction effects between various types of skilled labour.

Chapter 4 focuses specifically on one type of specialized labour that is often described as integral to urban competitiveness—highly educated workers in S&E occupations. Multivariate regressions are used to investigate variability in the growth of S&E employment. We estimate a partial adjustment model that examines the link between S&E growth and a set of initial factors. Of particular interest is the relationship between S&E growth and the amount of cultural employment in different cities at the beginning of the analysis period—as cultural workers represent one possible amenity that has been posited to attract scientists and engineers to a location. We then estimate a first-difference model and a second-difference model to test for the effects of omitted variable bias and endogeneity, respectively. Chapter 5 concludes.

Two appendices follow the main text. Appendix A reports descriptive statistics and correlation tables for select analysis variables. Appendix B contains a supplementary analysis of endogeneity bias within our S&E growth models, focusing on the relationship between scientific and cultural employment.

2. Urban growth and human capital: A review of concepts and theory

Large scale statistical research on the relationship between the educational attainment of city residents and city growth is relatively recent.[1] It is based on the fundamental idea that creativity drives growth and that the geographic concentration of more highly skilled workers creates more ideas that can then be transmitted more rapidly. As a result, an urban economy with a more highly educated workforce is expected to have higher levels of productivity and productivity growth.

Much of the literature that links educational attainment with growth uses the term 'human capital' as shorthand. This is based, implicitly or explicitly, on the premise that human capital is highly correlated with higher levels of education. Human capital can also result from experience, and this is not accounted for in this formulation. We should also note that some readers may find the term 'human capital' off-putting, because of its implied instrumental treatment of human beings. Nevertheless, we will adopt the term human capital because of its accepted meaning within the literature on which this paper relies.[2]

The links between human capital and growth have been formalized by Glaeser and others.[3] These urban growth models suggest labour growth is a function of the change in the level of (multifactor) productivity of a city, which, in turn, depends on a set of city-specific characteristics that are treated as initial conditions. Productivity growth, it is argued, stems from both static and dynamic sources. Static sources refer to urban characteristics whose influence on productivity rises over time. For instance, rising returns to education imply the contribution of education to productivity has been rising over time. Dynamic sources are related to urban characteristics that touch off a set of productivity enhancing series of events. Jacob's (1969) contention that industrial diversity leads to the spreading application of new ideas across industries is an example of a dynamic source of productivity growth. In practise, no attempt is made to empirically disentangle these two sources of productivity growth other than through the identification of variables that are thought to be more associated with one than the other.

Much of this literature has focused on the role of human capital as a driver of long-run employment (or population) growth. Glaeser (1994), Glaeser, Sheinkmen and Sheifer (1995), and Glaeser and Saiz (2003) have found that long-run urban growth is positively associated with initial skill endowments. These results have been shown to be robust to endogeneity bias (see Glaeser and Saiz 2003, and Shapiro 2005). This link between human capital and economic growth has been corroborated in other studies (see Glaeser 2000 and Florida 2002b for discussion).

1. For a more extensive review of the literature on human capital and urban development, see Florida (2002b).
2. We considered using Florida's term 'talent', but decided it too was flawed as it implied, in the context of this paper, that those with degrees had talent and those without somehow did not.
3. See Glaeser (2000) for a succinct discussion of these models.

These studies often utilize fairly broad measures of human capital, such as the percentage of an urban population that has attained postsecondary degrees. This reflects a general, and seemingly uncontroversial, view that a diverse mixture of skills and competencies is required to support the growth process. Locations obtain these skills and competencies by having large numbers of educated residents at work in broad industrial and occupational cross sections of the local economy. A potential contribution of Florida's recent work on human capital (2002a and 2002b) rests with its parallel emphasis on more restrictive measures of human capital, such as 'bohemians' and 'creative classes,' that comprise more narrowly defined urban subpopulations. Florida's work has led to much speculation over whether some types of human capital are more important for urban development than others, and how different types of human capital interact. A widely cited aspect of Florida's research is the link between technological and cultural creativity—that the strength of a city's cultural and artistic environment is positively correlated with emergence of a high-technology base (Florida 2002a, 2002b).

This paper makes two contributions to the literature on growth and human capital. First, our analysis of the growth process centres on disentangling the relative contributions made by broad and specialized forms of skilled labour. Recent empirical research (see Glaeser and Saiz 2003) has evaluated the importance of skilled workers writ large, by relying on measures of educational attainment to differentiate between cities with higher- and lower-quality workforces. Florida's recent work has delved into this more deeply, effectively by asking whether certain varieties of human capital are more important for growth than others.

In this paper, we are particularly interested in the role of scientists and engineers as drivers of urban growth. This group of workers is seen by many as essential to innovation. For instance, the Progressive Policy Institute begins its analysis of changes in engineering and science employment by noting that "…[t]echnological innovation is one of the key drivers of overall economic progress, and it is fueled by a strong engineering and scientific workforce." (Atkinson and Court, 1998: 41). Similarly, the National Science Foundation notes that scientists and engineers "contribute enormously to technological innovation and economic growth, research, and increased knowledge." (National Science Board, 2004: Chapters 3, 5) Here we are interested in directly testing the link between scientists and engineers and urban employment growth.

To our knowledge, relatively little work has been done on evaluating how different forms of human capital complement one another. Our analysis of urban growth evaluates whether the contribution that different types of specialized labour make to the growth process depends on their interaction with other skilled workers. This is consistent with the view that a diverse mix of complementary skills is required for growth (Jacobs 1969). While a seemingly uncontroversial premise, these interaction effects are understudied.

If it should turn out that scientists and engineers are important drivers of growth, then we are naturally interested in what factors attract them to particular cities. That is, we are interested in the identification of the (spatially) disequilibriating forces that will advantage one particular location over another.

These forces can take the shape of pecuniary and non-pecuniary incentives. Pecuniary incentives likely relate to an economic shift that results in an advantage of one location over another. For instance, if a mix of labour emerges in a city that raises the productivity of scientists and engineers, market wages of scientists and engineers will rise in response, resulting in an inflow of scientists and engineers to take advantage of these wage increases. This wage rise may or may not be temporary, depending on the elasticity of their labour supply curve.

Alternatively, incentives can be non-pecuniary and these relate largely to amenities. Florida (2002a, b) identifies amenities as a key factor that attracts the 'creative class,' of which scientists and engineers are an important part, to particular cities. Empirically, amenities have also been identified by others as important factors driving growth in cities (Rappapore 2006, and Glaeser, Kolko and Saiz 2001). Amenities can take the form of cultural activities, climate or, as Florida argues, a social environment that has low barriers to entry for newcomers with diverse lifestyles. Regardless of the source, these amenities can act as a source of disequilibrium, even if they are fixed. For instance, Rappapore argues climate may be rising in importance as incomes rise and climate becomes relatively more important compared with other sources of utility. We estimate a partial adjustment model to account for these disequilibrating forces (see Chapter 5).

3. Human capital, urban amenities and employment growth

In this chapter, we investigate the correlates of long-run employment growth in North American cities. Our tabulations are based on a panel of 242 cities constructed from the Canadian and U.S. Censuses of Population. Data on Canadian cities are derived from 1981, 1991 and 2001 Canadian Census files and data on U.S. cities are obtained from the 1980, 1990 and 2000 U.S. Census files. These data sources provide detailed information on the locational, educational and occupational characteristics of different classes of workers.

Our base measure of urban growth is the change in total paid employment from 1980 to 2000. Following Lucas (1988) and Glaeser (1994), we posit that differences in long-run urban growth depend on variations in the amount of human capital found in different cities, evaluated in the initial period. In what follows, we measure the importance of human capital in two ways. First, we use a general indicator of human capital based on the number of degree holders located in different urban areas in 1980 and 1981. This provides us with a broad-based measure of skilled labour at the onset of the analysis period.

Second, we examine the contribution to growth made by more specialized types of skilled labour. To do this, we divide our estimates of urban degree holders into different subgroups based on their occupational characteristics. These include (1) degree holders employed in science and engineering (S&E) occupations, (2) degree holders employed in cultural and heritage occupations, and (3) the residual category of degree holders employed in all other (non-S&E and non-cultural) occupations. These estimates of specialized labour (scientists and engineers and culture workers) are constructed using occupational taxonomies developed by the National Science Foundation and Statistics Canada.[4] For a description of S&E occupations and cultural occupations, see Tables 1 and 2.

4. For an overview of the science and engineering classifications, see Beckstead and Gellatly (2006); for culture and heritage occupations, see Statistics Canada (2004).

Table 1
Science and engineering occupations

Computer and mathematical scientists
Computer and information scientists
Mathematical scientists
Life and related scientists
Agricultural and food scientists
Biological and medical scientists
Environmental life scientists
Physical and related scientists
Chemists, except biochemists
Earth scientists, geologists and oceanographers
Physicists and astronomers
Other physical and related scientists
Social and related scientists
Economists
Political scientists
Psychologists
Sociologists and anthropologists
Other social and related scientists
Engineers
Aerospace and related engineers
Chemical engineers
Civil and architectural engineers
Electrical and related engineers
Industrial engineers
Mechanical engineers
Other engineers

Source: The National Science Foundation.

Taken together, scientists and engineers and people employed in culture occupations closely parallel what Florida describes as the core of the 'creative class' (see Florida 2002a, 328). The main difference between Florida's creative class and our specialized group of scientists and engineers and cultural labour is that we define this occupational group strictly in terms of degree holders throughout the analysis. We also test for the effect of including workers in these occupations without degrees.

Our growth models control for a range of urban amenities that proxy basic differences in the attractiveness of specific locations. We have estimated amenities both directly and indirectly. Following Glaeser, Kolko and Saiz (2001), amenities can be estimated indirectly by examining the willingness of consumers to pay for housing relative to income levels. They argue that, on the margin, variation in housing prices, while conditioning on income levels, will reflect variation in amenities across cities.

Table 2
Cultural occupations

Creative and artistic production occupations
Architects
Landscape architects
Industrial designers
Writers
Editors
Journalists
Producers, directors, choreographers and related occupations
Conductors, composers and arrangers
Musicians and singers
Dancers
Actors
Painters, sculptors and other visual artists
Photographers
Other performers
Graphic designers and illustrating artists
Interior designers
Theatre, fashion, exhibit and other creative designers
Artisans and crafts persons
Heritage collection and preservation occupations
Librarians
Conservators and curators
Archivists

Source: Statistics Canada (2004).

Accordingly, we constructed an amenities index from 1980 and 1981 census data using data on median housing values and median income for residents of owner-occupied dwellings.[5] The basic premise would be that after conditioning on household income, variation in home prices across cities would be a function of the relative attractiveness of these places. Hence amenities (A) would be given by

$$A = HP - E(HP) \qquad (1.1)$$

where *HP* is the house price and *E(HP)* is the expected house price conditioning on income *I*:

$$E(HP) = a + bI. \qquad (1.2)$$

The residuals obtained from (1.2) yields a continuous ranking of cities based on the estimated variation in urban amenities.

5. Note that since we are comparing data on house prices and employed incomes from Canada and the United States, we had to convert data denominated in Canadian dollars to U.S. dollars. We did so by purchasing power parity prices.

We evaluated our amenities index by correlating it with more direct measures of amenities from other data sources. These included measures of climate, violent crime and culture employment.[6] Two variables are used to measure the variation in temperature conditions across cities. The first is a city-specific measure of heating-degree days, the accumulated average daily temperature below 18 degrees Celsius, expressed as a daily average. The second is the analogous measure of cooling-degree days—the accumulated average daily temperature above 18 degrees Celsius, again converted to a daily average. Both climate variables are constructed using temperature data from the last 30 years.

Our amenities index is negatively correlated with heating degree days and positively correlated with the size of cultural employment (see Appendix A, Table A2). Murder rates, our proxy for violent crime, were not correlated with our amenities index. Each of these relationships was apparent when we regressed our amenities index against the set of direct measures.[7]

These correlations suggest the index is able to capture various amenities, and because it can capture a host of amenities that are difficult to measure directly—for example, quality of schools—it may be better than more direct measures. However, because this is a 'residual' measure, it is vulnerable to the effect of other factors that might affect house prices after conditioning on income levels. For instance, if individuals with higher levels of human capital have a preference for amenities and the presence of human capital and restrictions on housing supply are correlated, we may find a significant correlation between our amenities index and human capital that is an artefact of how the index was constructed. Keeping this in mind, we also substitute more direct measures of amenities for the amenities index to test the consistency of our models.

Our basic urban growth model posits that the long-run variation in employment growth across cities depends on initial differences in human capital and urban amenities. In Table 3, we report differences in average employment growth among cities with different human capital and amenity profiles.[8] We classify our sample into cities that fall above and below the median, based separately on the share of employment accounted for by degree holders, the share of employment accounted for by degree holders in S&E occupations, the share of employment accounted for by degree holders in cultural occupations, and the value of the amenities index. Each of the human capital variables was measured in 1980 and 1981. We report average annual growth rates for cities in each stratum, along with rates at different points in the distribution of growth rates.

6. Data were obtained from Environment Canada (www.on.ec.gc.ca) and the National Oceanic and Atmospheric Administration (NOAA) (www.noaa.gov) for the climate variables, Statistics Canada and the FBI for violent crime, and the Canadian and U.S. Censuses for culture employment.
7. We also examined a series of more sophisticated regression models to measure amenities that took into account other factors that might affect housing prices, such as negative shocks to employment. We found that the amenities indexes derived from these estimates provided qualitatively similar results, and thus we utilized the simpler model.
8. Descriptive statistics on these variables are found in Appendix A, Table A1.

Table 3
Average annual employment growth rate, 1980 to 2000, by select classification variable

	Average annual growth rate	Average annual growth rates, select quantiles				
		10th	25th	Median	75th	90th
All cities	1.78	0.40	0.94	1.62	2.39	3.50
Human capital variables						
Share of workers with post-secondary degrees						
Above median	1.99[1]	0.71[1]	1.24[1]	1.84	2.49	3.54
Below median	1.57[1]	0.11[1]	0.72[1]	1.51	2.18	3.40
Share of degree holders employed in science and engineering occupations						
Above median	1.82	0.58	0.99	1.70	2.40	3.36
Below median	1.74	0.20	0.81	1.59	2.36	3.51
Share of degree holders employed in cultural occupations						
Above median	2.03[1]	0.76[1]	1.26[1]	1.84	2.53	3.87
Below median	1.52[1]	0.14[1]	0.71[1]	1.47	2.19	3.06
Urban amenities index						
Above median	2.13[1]	0.76[1]	1.42[1]	2.04[1]	2.60[1]	3.87
Below median	1.42[1]	0.14[1]	0.70[1]	1.32[1]	1.98[1]	2.94

1. Differences between pairs are statistically significant at the 5% level of confidence.
Sources: Canadian Census 1981 and 2001 and U.S. Census 1980 and 2000.

The average annual rate of employment growth for cities in our sample is 1.8%. Cities with larger concentrations of degree holders—measured as a percentage of the local employment base—have, on balance, experienced faster employment growth—2.0% per annum—than cities with smaller relative concentrations of degree holders—1.6%. These differences may appear to be small but, due to compound growth, over the 20-year study period a city that grew at 2% would grow by 49%, while a city with a growth rate of 1.6% would grow by a more modest 37%. Substantial differences in average growth occur when classifying cities on the basis of cultural employment and urban amenities. Smaller differences in average growth are apparent when stratifying cities on the basis of their S&E employment shares. This result runs counter to our expectation that cities with a strong science and engineering base would see significantly stronger growth than cities without. As will become apparent in the multivariate analysis to follow, the relationship between S&E employment and growth is much more nuanced.

The quantile estimates in Table 3 suggest that large differences in growth rates often occur at the lower end of the growth distribution. Low-growth cities with above-median concentrations of degree holders exhibit stronger growth—0.7% per annum at the 10th percentile and 1.2% at the 25th percentile—than do low growth cities with below-median concentrations of degree holders—0.1% and 0.7%, respectively. When our sample is stratified on the basis of S&E employment shares, larger differences in growth rates are only apparent at the 10th percentile. However, these are not statistically significant. More sizable differentials occur at all points in the growth distribution when classifying cities on the basis of cultural workers or amenities. In general, the quantile estimates suggest higher ranks across the various correlates of growth, while not guaranteeing spectacular growth rates, do serve to insulate cities from excessively low growth rates—in effect, they act as a floor.

The bivariate tabulations in Table 3 suggest that long-run differences in employment growth across cities are correlated with underlying differences in skilled labour and urban amenities, evaluated in the initial period. Below, we examine the strength of these relationships via a series of regressions. Six different specifications are reported in Table 4. These reflect different approaches to modelling the contribution of human capital to growth and the inclusion of different control variables.[9]

In all models we estimate employment growth as a function of initial conditions:

$$\ln\left(E_{jt}/E_{jt-1}\right) = \alpha + \mathbf{X}_{jt-1}\boldsymbol{\delta} + \mathbf{Z}_{jt-1}\boldsymbol{\beta} + \varepsilon_j \qquad (1.3)$$

where E is employment indexed by year t and $\mathbf{X}_t$ is a vector of human capital characteristics and $\mathbf{Z}_t$ is a vector of other urban characteristics (e.g., amenities). We utilize the natural logarithm of employment growth in order to de-emphasize the effect of high rates of growth, which are often associated with relatively small units, on the regression coefficients. As noted above, other studies that have attempted to control for the endogeneity of human capital and growth have shown the positive association between human capital (usually, as measured by the share of degree holders) on growth to be highly robust. Thus we estimate the model under the assumption that endogeneity is not an issue, at least as it applies to our human capital variables. All continuous variables in Table 4—and Equation (1.3)—are expressed in their natural logarithmic form.

The first specification (Column 1) estimates employment growth on degree share. In this simple bivariate regression, human capital is positively associated with growth, with an estimated elasticity of 0.18. Column 2 then controls for the variation in heating- and cooling-degree days—two direct measures of urban amenities that are clearly exogenous to the growth process. Heating-degree days are negatively associated with employment growth, while the effect of cooling-degree days is insignificant. The estimated elasticity on degree share declines slightly to 0.16, but remains significant.[10]

In Column 3, we evaluate the impact of more specialized types of human capital on employment growth by dividing degree holders into three mutually exclusive subgroups: degree holders in S&E occupations, degree holders in culture occupations, and other degree holders. As in Column 2, we control for the variation in heating- and cooling-degree days. None of these occupational subgroups exerted a significant impact on growth. It should be noted, however, that these occupational subgroups are highly correlated with one another. The S&E share and the culture share have a correlation coefficient of 0.60, while the correlation between the other degree variable and the S&E and culture shares is 0.56 and 0.78, respectively.[11] It is also worth noting that the other degree variable is almost perfectly correlated with the original degree share, as the occupational categories omitted from this other degree variable—scientists, engineers and other cultural workers—represent a very small percentage of employed degree holders.

9. For correlation tables, see Appendix A, Table A2.
10. These two climate variables exhibit very little correlation with our human capital variables (see Appendix A, Table A2).
11. All correlations are estimated using the natural logarithmic transformation of these shares; see Appendix A, Table A2.

Column 3 assumes that these different types of skilled labour contribute separately to growth. In Column 4, we posit that the overall contribution of any one group of employed degree holders depends on its interaction with other groups. Following Jacobs (1969), we posit that growth requires a diversity of complementary skills. Naturally, this suggests we should interact the shares of workers across our three groups. Four interaction terms are included that evaluate the importance of different human capital combinations: three that focus on cross-products between science and engineers, cultural workers and other degree holders; and one that captures the joint product of all three groups.

The interpretation of the coefficients on the human capital terms requires some explanation. When these interaction terms are included in the model, the partial effect of a change in any one category (e.g., other degree holders) on growth depends both on its direct contribution and on the indirect contributions that stem from interactions between this group of interest and other types of skilled labour. Hence the impact of changes in other degree holders (*odh*) on growth can be expressed in general terms as

$$\frac{\partial\left(e_t - e_{t-1}\right)}{\partial(odh_{t-1})} = \beta_1 + \beta_2 se_{t-1} + \beta_3 culture_{t-1} + \beta_4\left(se_{t-1} \times culture_{t-1}\right) \qquad (1.4)$$

where all variables have been transformed into their natural logarithmic form. In this formulation β_1 is the coefficient on the other degree holders term, and β_2 and β_3 capture the indirect contributions that scientists and engineers and cultural workers, respectively, have in determining the overall impact of other degree holders on growth. Similarly, β_4 measures the joint interaction between these two groups.

This interactive model yields better evidence that differences in human capital are correlated with long-run employment growth after controlling for differences in climate. The coefficient on the other degree holder term is positive and significant, and the interaction between S&E degree holders and other degree holders is significant at the 6% level of confidence. As before, heating-degree days is negatively associated with growth.

In Column 5, we re-estimate the interaction model in Column 4 with additional controls. Two of these—population size in 1980 and an index of industrial diversity in 1980[12]—are designed to control for the general relationship between agglomeration economies and growth. The log of population is intended to capture the effect of urban size on static agglomeration economies (e.g., the impact of shared infrastructure assets on productivity). Industrial diversity is included to capture Jacob's dynamic urbanization economies, which have been identified by others as important drivers of growth (see Quigley 1998 for a review of this literature). We also include binary variables for Canada and capital city (country, province or state) to capture country-

12. We utilize an entropy-based measure of industrial diversity given by:

$$NE_j = \exp\left[\sum_i s_{ij} \ln\left(1/s_{ij}\right)\right]$$

, where *sij* is the share of employment in industry *i* in metropolitan areas *j*. The *NE* is interpreted as the number of industries that would be present in a metropolitan area if employment were evenly distributed across all industries.

specific effects (e.g., demographics and immigration policies) and the influence of the seats of local or national government on growth.

The inclusion of these controls reduces the coefficients on the human capital variables. Only those on the non-interacted S&E and degree holder shares, and on their interaction term, remain significant at the 10% level. Employment growth is negatively associated with city size and heating degree days, and is more apparent in Canadian cities. It is only weakly influenced by industrial diversity, which is somewhat surprising, because other studies have found a significant and positive effect. However, we are already capturing part of the effect of industrial diversity through our interaction terms for the degree holder variables. It should also be kept in mind that the variation in industrial diversity across cities is relatively small for cities over 100,000 in population. Most of the increase in industrial diversity occurs as cities increase in size from 10,000 to 100,000 (see Beckstead and Brown 2003).

Columns 2 through 5 provide some evidence that the long-run growth of cities is influenced by climate, as, other things equal, cities with more heating-degree days exhibit slower employment growth. The elasticity estimate on heating-degree days, at about 0.1, is robust to changes in specification. In contrast, cooling-degree days have no effect on employment growth in any of our models. In Column 6, we replace these two direct measures with the indirect amenities index that we obtained from regressing housing prices on income (Equation [1.2]). As noted earlier, this derived index is designed to measure a broad cross-section of urban amenities—in effect, the amalgam of all factors (physical, social or cultural) that together affect the perceived attractiveness of different cities. This index variable has an estimated elasticity of 0.3, which provides much stronger evidence that differences in urban amenities are correlated with growth.

Substituting this amenities measure for the two climate variables better isolates the relationship between human capital and growth. The coefficients on S&E-degree holders, other-degree holders, and their interaction term are all positive and significant, while the joint product of all degree subgroups is positive and weakly significant. These interaction terms measure complementarities—the gains associated with combining different types of skilled labour. The positive interaction between S&E workers and other-degree holders suggests that cities with large concentrations of both types of workers may, other things being equal, exhibit faster growth than those that specialize more in one or the other type. We can estimate the net contribution of any one group of skilled workers by solving out the direct and indirect effects in a manner consistent with Equation (1.4).

When we evaluate each of the log degree shares at their respective medians, other degree holders have the strongest estimated effect on employment growth. The implicit elasticity associated with other-degree holders is 0.2. This stands in sharp contrast to the implicit elasticities of -0.06 and -0.04 that we obtain for S&E and cultural workers, respectively. These latter two estimates suggest that there is very little direct relation between these specific kinds of human capital and employment growth.

Table 4
Urban employment growth, 1980 to 2000

	Growth in total employment—1980 to 2000											
	(1)		(2)		(3)		(4)		(5)		(6)	
All degree holders share	0.177	(0.005)	0.162	(0.011)	…	…	…	…	…	…	…	…
Science and engineering (S&E) degree share	…	…	…	…	-0.034	(0.422)	2.416	(0.088)	2.214	(0.090)	2.555	(0.053)
Culture degree share	…	…	…	…	0.078	(0.099)	1.793	(0.091)	1.100	(0.272)	1.304	(0.218)
Other degree holder share	…	…	…	…	0.079	(0.398)	5.822	(0.041)	4.597	(0.082)	5.762	(0.038)
Other degree holder share x S&E degree share	…	…	…	…	…	…	1.330	(0.060)	1.179	(0.075)	1.463	(0.031)
Other degree holder share x culture degree share	…	…	…	…	…	…	0.951	(0.071)	0.554	(0.274)	0.778	(0.147)
S&E degree share x culture degree share	…	…	…	…	…	…	0.405	(0.135)	0.306	(0.228)	0.377	(0.147)
Other degree holder share x S&E degree share x culture degree share	…	…	…	…	…	…	0.220	(0.089)	0.159	(0.194)	0.214	(0.090)
Amenities index	…	…	…	…	…	…	…	…	…	…	0.308	(0.000)
Heating degree days (30 year average)	…	…	-0.100	(0.008)	-0.098	(0.010)	-0.103	(0.006)	-0.111	(0.002)	…	…
Cooling degree days (30 year average)	…	…	-0.023	(0.250)	-0.022	(0.293)	-0.027	(0.201)	-0.010	(0.666)	…	…
Population	…	…	…	…	…	…	…	…	-0.049	(0.031)	-0.035	(0.112)
Industrial diversity index	…	…	…	…	…	…	…	…	0.161	(0.126)	0.110	(0.296)
Canada (binary variable)	…	…	…	…	…	…	…	…	0.136	(0.023)	0.048	(0.405)
Capital city (binary variable)	…	…	…	…	…	…	…	…	0.001	(0.981)	0.012	(0.786)
Intercept	0.664	(0.000)	0.822	(0.000)	0.943	(0.000)	11.316	(0.036)	9.243	(0.060)	10.038	(0.051)
F statistic	7.9		5.3		3.5		2.8		2.9		3.1	
Probability > F	0.005		0.001		0.004		0.003		0.001		0.001	
R2	0.034		0.097		0.107		0.126		0.167		0.159	
Number of observations	242		242		242		242		242		242	

… not applicable
Notes: All explanatory variables are measured in 1980, unless otherwise specified. Heteroskedasticity corrected p-values are in parentheses.
Sources: Canadian Census 1981 and 2001; United States Census 1980 and 2000. Data on climate were obtained from Environment Canada (www.on.ec.gc.ca) and the National Oceanic and Atmospheric Administration (NOAA) (www.noaa.gov).

In contrast, the positive interaction term between scientists and engineers and other degree holders suggests that changes in the amount of S&E employment may exert a stronger impact on growth through its impact on the other degree group. To see this, we re-calculate the implicit elasticity associated with other-degree holders, this time evaluating the log science and engineering term at the 10th and 90th percentile of the distribution—raising the S&E share of employment from 0.7% to 2.7%. The impact on the net elasticity associated with other-degree holders was substantial, reducing the net estimate from 0.20 to -0.04 for a share of scientists and engineers at the 10th percentile, while increasing it to 0.45 at the 90th percentile. This suggests that the importance of scientists and engineers is best measured through their impact on broader forms of human capital. However, it is important to keep in mind that these calculations are based on point estimates. The confidence interval around these may be quite high.

Florida has argued that workers that comprise the 'creative class'—especially those that constitute the creative core (scientists and engineers and culture-based occupations)—have a particularly strong influence on growth. He also argues that 'bohemians' (which are largely made up the cultural component of the creative class) have an abnormally strong effect on growth. Florida's assertions have been countered by Glaeser (2004). Glaeser shows that there is no independent effect of either the creative class or bohemians on growth, after controlling for the share of degree holders. Our findings suggest that we should take a more nuanced view of the relationship between particular types of human capital and growth. That is, it is the broad set of degree holders that consistently drive growth, but the effectiveness of this group is enhanced when combined with a higher share of scientists and engineers. There is less evidence that culture occupations, on their own or through interactions with other forms of human capital, have a particularly strong impact on growth. The general conclusion to be drawn here is that it is not only the prevalence of human capital in a city that matters, but the mix as well.[13] In the next chapter, we extend our analysis of human capital by asking what factors help fuel the growth of a city's science and engineering workforce.

13. We also examined whether our results are robust to one other major definitional issue concerning our measures of specialized human capital—the impact of modifying our definitions of workers in S&E and cultural occupations to include non-degree holders as well as degree-holders. This has a relatively small impact on the scope of our science and engineering definition—as the vast majority of S&E workers possess university degrees. But is has a major impact on the scope of the cultural definition, as non-degree holders represent a much larger percentage of workers in cultural occupations. We evaluated these changes by again re-estimating our final specification, Column 6 in Table 4, using these modified definitions. On balance, these changes had little impact on the estimated relationships.

4. The determinants of science and engineering employment growth

Scientists and engineers have long garnered much attention in the literature on industrial competitiveness. These workers are widely regarded as integral to innovation and technological progress. Their importance is generally portrayed as axiomatic. In the previous chapter we found that scientists and engineers contribute positively to long-run employment growth when these high-technology workers are found alongside others with high levels of human capital. The question of what factors influence scientists and engineers to concentrate in some cities and not others naturally follows from this. Here we again build on Florida's work, all the while seeking to increase our confidence that the urban correlates that are associated with science and engineering (S&E) employment growth are unbiased.

Our empirical strategy for investigating S&E growth centres on three separate regression exercises. First, we estimate a partial adjustment model that evaluates growth as a function of a set of initial conditions. This model explicitly attempts to incorporate the effects of disequilibriating conditions on S&E employment growth. Second, we estimate a first difference model in which changes in S&E employment are evaluated against contemporaneous changes in our time variant regressors. Third, we evaluate whether differences in S&E growth across discrete time periods depend on the growth of other factors in the initial period. Together these exercises go some way toward handling the issues of endogeneity and unobserved fixed effects that hamper empirical research in this area.

We begin by proposing one possible mechanism for evaluating differences in S&E growth. Heuristically, S&E growth can be represented as a partial adjustment model given by Equations (1.5) and (1.6):

$$SE^{*}_{t-1} = \alpha_0 + \alpha_1 x_{t-1} + \varepsilon_{t-1} \quad (1.5)$$

$$SE_t - SE_{t-1} = \lambda\left(SE^{*}_{t-1} - SE_{t-1}\right) + \nu_t. \quad (1.6)$$

Equation (1.5) describes the relationship between an independent variable (x_{t-1}) and the equilibrium level of S&E employment in a specific location in year *t*-1. In more concrete terms, the expectation is that a higher level of *x*, (e.g., other degree holders or cultural employment) will allow an urban area to sustain a higher level of science and engineering employment. Equation (1.6) describes the adjustment that takes place in the level of S&E employment when it deviates from the equilibrium level, where λ can be interpreted as the rate of adjustment. Therefore, if the expected level exceeds the actual level in the previous period, we would anticipate S&E employment to increase. Substituting (1.5) into (1.6), we obtain

$$SE_t - SE_{t-1} = \beta_0 + \beta_1 SE_{t-1} + \beta_2 x_{t-1} + \mu_t \quad (1.7)$$

where,

$$\beta_0 = \lambda\alpha_0;$$
$$\beta_1 = -\lambda;$$
$$\beta_2 = \lambda\alpha_1;$$
$$\mu = \lambda\varepsilon_{t-1} + \nu_t$$

Equation (1.7) specifies that the growth in S&E employment from *t*-1 to *t* depends on the initial level of S&E employment and a vector of other characteristics at *t*-1. We use this model to estimate S&E growth.

From an econometric perspective, the partial adjustment model specified in (1.7) has both advantages and disadvantages. It is advantaged, at least over cross-sectional models, because it goes some way toward dealing with the endogeneity of many of the right-hand-side variables.[14] For instance, the direction of causality between culture employment and S&E employment is not clear. Its obvious disadvantage stems from the fact that it does not control for unobserved fixed effects.

We should also note that our specification assumes that it takes a long period of time (a decade) for urban economies to adjust to disequilibriating shocks. We believe this assumption is reasonable. Consider two cities, A and B, which are equal in all respects, except that A has recently improved its cultural amenities.[15] As a result, entrepreneurs in A will be able to hire scientists and engineers with more education and experience for the same wage, providing these entrepreneurs with an advantage over those in B. This will eventually shift market share from firms in B to firms in A. These market-share shifts, however, will likely take years to become discernable, as it takes considerable time for labour to adjust across space and firms to convert their labour advantage into market opportunities.

Our vector of city-characteristics includes two sets of variables. The first is a diverse range of controls that are posited to influence S&E growth. These include the level of other degree holders (i.e., all employed degree holders in non-science and non-cultural occupations), the number of post-secondary educators, and the size of the urban population. We include other degree holders because of the strong complementarities that are apparent between this general

14. We do not believe the partial adjustment model addresses the issue of endogeneity completely. To see why it is important to fix in our minds where endogeneity likely originates in this context, consider a city where S&E growth can be traced back to the establishment of a large research-driven university (e.g., MIT) many decades in the past. This institution persists over time in stimulating above average growth in scientists and engineering employment. These workers are well paid and expend a relatively high proportion of their incomes on culture activities, leading to a large culture sector. The university itself may also fund some of these culture activities through various arts programs. As a result, we observe an association between the share of culture employment and S&E growth in the partial adjustment model that can be traced back to the initial shock, rather than the attraction of a vibrant culture. In effect, the shock to S&E employment (though decades in the past) leads to a contemporaneous correlation between the model’s error and the coefficient on culture, biasing its estimates upwards.
15. We could equivalently assume A had a higher level of amenities, but tastes had changed making them more important.

class of degree holders and those employed in S&E occupations in Chapter 3. The impact of postsecondary educators is examined separately, because S&E growth may be related not to the ability of cities to attract scientists and engineers but to their ability to produce them. Population size is included to evaluate the link between S&E growth and agglomeration economies. We also include separate bivariate controls for Canada and capital city (country, state or province). The latter are included to capture any effects from the concentration of government spending in capital cities.

The second set of right-hand-side variables proxy those amenities that may serve to attract scientists and engineers to different locations. These include the number of heating- and cooling-degree days, the level of immigration, and the level of cultural employment (i.e., degree holders in cultural occupations). The climate variables and cultural employment are strongly associated with the amenities index used in Chapter 3. Immigrants are examined separately as a proxy for the openness (or tolerance) within cities (Florida 2002a, b).

We estimate Equation (1.7) for three separate time periods: 1980 to 1990, 1990 to 2000 and 1980 to 2000. All continuous variables are again expressed in log form, and all of the right-hand-side variables noted above are measured as initial levels as opposed to shares, in the main to reduce the degree of induced colinearity among the right-hand-side variables.

In Table 5, we also report separate results for total S&E growth (Columns 1, 2 and 3) and private sector S&E growth (Columns 4, 5 and 6). The private sector regressions include an additional covariate: the share of S&E employment in the initial period located in the non-business sector. This is included to capture the effect of government spending on S&E employment growth.

There is strong evidence of reversion to the mean within our S&E growth models. Cities with large initial levels of S&E employment experienced slower S&E growth. This effect was apparent in each analysis period, both when examining total S&E growth and private sector S&E growth. Large negative elasticities are apparent when evaluating the impact of S&E levels in 1980 on long-run growth from 1980 to 2000, and when evaluating private sector S&E growth during the 1990s. These results suggest that S&E growth follows a stochastic process in which specific cities are unlikely to sustain large relative increases over long periods.

The amount of human capital in cities is also a strong predictor of S&E growth. The initial size of the degree-holding population (excluding those science and cultural occupations) is positively associated with S&E growth in all but one analysis period. Once again, the largest elasticities are apparent over the full analysis period, when S&E growth from 1980 to 2000 is regressed on the level of degree holders in 1980. This strong association between these broad and specialized types of human capital is, in broad terms, consistent with the complementary effects observed in the urban growth models in Chapter 3.

Table 5
Growth in science and engineering degree holders – Partial adjustment models

	Growth in science and engineering (S&E) degree holders						Growth in S&E degree holders (business sector)					
Period	1980 to 1990		1990 to 2000		1980 to 2000		1980 to 1990		1990 to 2000		1980 to 2000	
S&E degree holders	-0.30	(0.000)	-0.36	(0.000)	-0.50	(0.000)	-0.20	(0.006)	-0.44	(0.000)	-0.45	(0.000)
Other degree holders	0.60	(0.012)	0.45	(0.038)	0.77	(0.003)	0.47	(0.081)	0.58	(0.010)	0.67	(0.014)
Post-secondary educators	0.01	(0.869)	-0.02	(0.704)	0.00	(0.946)	-0.01	(0.898)	-0.02	(0.804)	-0.01	(0.857)
Urban population	-0.15	(0.276)	-0.38	(0.007)	-0.38	(0.039)	-0.12	(0.422)	-0.42	(0.005)	-0.32	(0.099)
Bivariate variable for Canada	0.08	(0.519)	0.21	(0.083)	0.31	(0.033)	0.06	(0.655)	0.31	(0.016)	0.37	(0.020)
Bivariate variable for capital city	0.02	(0.674)	-0.02	(0.705)	0.00	(0.963)	0.01	(0.887)	0.01	(0.879)	-0.02	(0.821)
Share of S&E employment in non-business sector							0.03	(0.621)	-0.16	(0.001)	-0.01	(0.875)
Heating degree days (30 year average)	-0.13	(0.002)	0.07	(0.091)	-0.09	(0.117)	-0.11	(0.016)	0.07	(0.103)	-0.06	(0.358)
Cooling degree days (30 year average)	-0.10	(0.000)	0.05	(0.084)	-0.04	(0.355)	-0.11	(0.001)	0.05	(0.186)	-0.04	(0.443)
Immigrants	-0.01	(0.757)	0.03	(0.510)	-0.01	(0.717)	-0.02	(0.632)	0.04	(0.410)	-0.02	(0.635)
Cultural degree holders	-0.07	(0.514)	0.25	(0.002)	0.17	(0.050)	-0.03	(0.811)	0.24	(0.008)	0.22	(0.035)
Intercept	-0.68	(0.196)	1.49	(0.001)	0.84	(0.186)	-0.56	(0.334)	0.84	(0.101)	0.46	(0.522)
F	5.8		7.5		7.9		5.0		9.7		8.6	
Probability > F	0.000		0.000		0.000		0.000		0.000		0.000	
R-squared	0.21		0.22		0.28		0.18		0.26		0.28	
Number of observations	242		242		242		242		242		242	

Notes: All variables are measured in terms of the intitial period, unless otherwise specified. Heteroskedasticity corrected p-values are in parentheses.
Sources: Canadian Census 1981, 1991 and 2001; United States Census 1980, 1990 and 2000. Data on climate were obtained from Environment Canada (www.on.ec.gc.ca) and the National Oceanic and Atmospheric Administration (NOAA) (www.noaa.gov).

Results for the other variables are less robust across specifications. Climate factors were related to S&E growth during the 1980s, whereas cultural employment is positively associated with S&E growth in the 1990s (and over the full analysis period). We are particularly interested in the relationship between cultural and science workers because of Florida's assertion that high-technology workers congregate in cities with large creative or cultural cores. There is some evidence from these growth models that this is occurring, but these effects are limited to the 1990-to-2000 period. They are also qualitatively small, in relation to the impact of other-degree holders on S&E growth. The remaining issue is that of establishing the direction of 'causality' between changes in S&E employment and changes in culture employment. We address this by developing a second-difference model (see below) and by implementing a Granger causality test (see Appendix B).

The Granger test provides evidence that past culture employment, evaluated separately in 1990 and 1980, is positively associated with the level of S&E employment in 2000, after controlling for past variation in other possible covariates of S&E employment (i.e., other-degree holders, post-secondary educators, immigration, and population size). Conversely, there is no evidence from the Granger test that causality also runs in the opposite direction—namely, that past variation in S&E employment, evaluated in 1990 and 1980, is associated with the level of culture employment in 2000. Together these results are consistent with the premise of the partial adjustment models, in which the level of culture employment within a city is expected to influence the subsequent growth of its S&E workforce.

We find no relationship between the strength of postsecondary educator employment and the growth of S&E employment, irrespective of specification or whether we restrict scientists and engineers to the private sector. Hence, there appears to be little statistical connection between the ability of a city to generate scientists and engineers and their growth. However, this result may be influenced by the colinearity between postsecondary educators and other-degree holders.

Our regressions also find some evidence that S&E growth is negatively related to initial population size, after other factors are taken into account. In other work (Beckstead and Brown 2006), we have found a strong positive association between population size and S&E growth across North American cities. These findings suggest that this association is not independent of a set of other urban characteristics that are correlated with urban size. Finally, there is some evidence from these regressions that long-run S&E growth has been stronger in Canada, which is consistent with the aggregate trends (see Beckstead and Brown 2006).

As we have already noted, one important limitation of the partial adjustment models reported above is that they do not control for the presence of unobserved fixed effects. Below we estimate first difference models to examine how S&E growth correlates with contemporaneous changes in our time-variant independent variables, after the influence of fixed effects is removed. These models have the general form:

$$SE_t - SE_{t-1} = \alpha_0 + \alpha_1(x_t - x_{t-1}) + \mu_t. \quad (1.8)$$

We include in the first difference model the same time varying regressors used in the partial difference model, except for the initial level of S&E employment.

Table 6
Growth in scientists and engineers – First difference models

	Growth in science and engineering (S&E) degree holders						Growth in S&E degree holders (business sector)					
Period	1980 to 1990		1990 to 2000		1980 to 2000		1980 to 1990		1990 to 2000		1980 to 2000	
Δ in other degree holders	1.01	(0.000)	1.49	(0.000)	1.08	(0.000)	0.97	(0.000)	1.35	(0.000)	0.89	(0.000)
Δ in post-secondary educators	-0.05	(0.426)	-0.20	(0.010)	-0.31	(0.000)	-0.02	(0.767)	-0.18	(0.062)	-0.21	(0.006)
Δ in urban population	-0.33	(0.098)	-0.23	(0.081)	-0.07	(0.698)	-0.32	(0.269)	-0.17	(0.337)	0.04	(0.809)
Δ in share of S&E employment in non-business sector	…	…	…	…	…	…	-0.35	(0.000)	-0.36	(0.000)	-0.43	(0.000)
Δ in immigrants	0.26	(0.000)	0.05	(0.450)	0.20	(0.000)	0.17	(0.016)	0.04	(0.584)	0.16	(0.001)
Δ in cultural degree holders	0.17	(0.040)	0.00	(0.983)	0.11	(0.151)	0.24	(0.017)	0.05	(0.531)	0.09	(0.158)
Intercept	-0.02	(0.704)	0.07	(0.061)	0.16	(0.043)	0.003	(0.969)	0.10	(0.020)	0.27	(0.001)
F	33.6		32.1		51.3		42.1		28.0		60.6	
Probability > F	0.000		0.000		0.000		0.000		0.000		0.000	
R2	0.42		0.55		0.54		0.48		0.54		0.65	
Number of observations	242		242		242		242		242		242	

… not applicable
Note: Heteroskedasticity corrected p-values are in parentheses.
Sources: Canadian Census 1981, 1991 and 2001; United States Census 1980, 1990 and 2000.

Again there is strong evidence that faster S&E growth is more apt to occur in cities that demonstrate a strong overall commitment to developing their human capital. The estimated elasticities that capture the impact of changes in degree holders on S&E growth are large and significant in all cases (see Table 6). We should note that it is very difficult to distinguish the directionality of this relationship. Other-degree holders may follow the growth of scientists and engineers, or vice versa.

The results of the first-difference model also suggests there is a trade-off between public and private sector S&E employment, as shifts in the public sector share are negatively correlated with changes in the level of private sector S&E growth.

Relationships between S&E growth and contemporaneous changes in other variables are, on balance, less robust. Both total and private sector S&E growth are positively associated with the growth in immigration during the 1980s. And private sector S&E growth is positively correlated with the growth in immigration over the full period.

Other results apparent over the longer term pertain to the impact of city size and postsecondary educators. City growth is negatively correlated with total S&E growth from 1980 to 2000. Similarly, increases in postsecondary educators are negatively associated with private sector S&E growth. The negative association with postsecondary educators is puzzling because we would have expected the supply of scientists and engineers to increase with this group. There is little evidence of a strong link between changes in cultural and S&E employment from these first difference models, beyond a positive correlation during the 1980s.

While the first difference models in Table 6 remove the possible bias associated with unobserved fixed effects, they reveal little about the underlying causal process that links the growth in scientists and engineers to other forms of human capital. The partial adjustment models reported in Table 1 address the issue of causality in a rudimentary way—by evaluating differences in S&E growth based on the variation in the correlates at the beginning of the analysis period. As we noted, however, the presence of unobservable fixed effects (ranging from physical amenities to good governance) can hamper the interpretability of these models. In this final set of models, we attempt to deal with both unobserved fixed effects and endogeneity at the same time.

Here we focus on the changes in S&E growth that occur between our two sub-periods—1980 to 1990 and 1990 to 2000. We subtract our estimate of S&E growth in the first period from S&E growth in the second period to obtain a measure of the acceleration (or deceleration) in S&E growth that cities experienced in the 1990s, relative to the amount of S&E growth that occurred in the 1980s. We then regresses these growth differentials on the growth in each of our time variant covariates during the 1980s. In effect, we are differencing Equation (1.7):

$$\Delta\Delta \ln SE_{t-1,t,t+1} = \delta_0 + \delta_1 \Delta \ln SE_{t,t-1} + \delta_2 \ln \Delta x_{t,t-1} + \varepsilon_{t-1,t,t+1}. \qquad (1.9)$$

In so doing, we effectively ask whether an increase in an explanatory variable leads to an acceleration or deceleration in the growth of S&E employment. It is less likely that this is due to the endogeneity of culture employment, for instance, as we are associating an increase in culture employment with an acceleration in S&E employment. That is, any shock that results in an acceleration of S&E employment will not be related to some historically generated process (see Footnote 10). Hence, any acceleration in S&E employment growth is more likely to be linked to an increase in amenities traced to culture employment. Furthermore, because the model is defined strictly in terms of growth variables, it also addresses the problem of unobserved fixed effects. Results are presented in Table 7.

These regressions again demonstrate that the growth in S&E workers was strongly influenced by a process of mean reversion. Cities that experienced fast S&E growth in the 1980s were more likely to experience slower growth in the 1990s. This had a much larger impact on the growth differential than any other factor.

There is some evidence that the growth of other-degree holders that cities experienced in the 1980s effected an acceleration of private sector S&E growth in the 1990s. Cities that increased their human capital during the first decade were likely to experience stronger private sector S&E employment in the 1990s than in the 1980s. This effect is not apparent when examining all S&E workers.

Shifts in the sectoral composition of the local S&E workforce also affect the magnitude of private sector S&E growth. Cities that increased their public sector S&E shares in the 1980s had slower private sector S&E growth in the 1990s compared with the previous decade. This is likely the result of defence cuts in U.S. cities whose private sector S&E workforces depended on contracts from the U.S. government.

The growth in immigration during the 1980s is weakly related to subsequent changes in both total S&E growth and private sector S&E growth. Cities with more immigration experienced stronger S&E growth in the 1990s. This is consistent with immigrants creating either a pool of cheap labour and/or a pool of entrepreneurial talent. This finding is also consistent with Florida’s contention that a large immigrant share is an indicator of a diverse cosmopolitan city that is particularly attractive to highly skilled workers, like scientists and engineers.

The results in Table 7 also indicate that the growth in cultural workers that occurred during the 1980s did not produce any subsequent variation in S&E growth performance in the 1990s. This result was apparent when examining total S&E growth or business sector S&E growth.

The objective of this chapter was to develop a set of models to statistically explain the growth of S&E employment during the 1980-to-2000 period across cities, while trying to address some of the more troublesome econometric issues that are germane to this type of analysis. In general, we find a consistent relationship between S&E growth and our broader proxy for human capital, other-degree holders. This suggests S&E growth is, at least in part, driven by the complementarities that result from combining broad and specialized forms of human capital. Less consistent is the link between S&E growth and amenities, as measured by climate, culture and, immigrants, who are sometimes included in urban growth models to proxy openness. Our models also suggest that S&E growth follows a stochastic process of mean reversion—that is, a high level of S&E employment or S&E growth in one period is often followed by weaker growth in the subsequent period.

Table 7
Science and engineering growth differential models

	Science and engineering (S&E) growth differential			
	1990s minus 1980s		1990s minus 1980s (business sector)	
Δ in S&E degree holders	-1.24	(0.000)	-1.31	(0.000)
Δ in other degree holders	0.20	(0.378)	0.46	(0.059)
Δ in post-secondary educators	-0.11	(0.352)	-0.12	(0.343)
Δ in urban population during	-0.21	(0.307)	-0.34	(0.098)
Δ in share of S&E employment in non-business sector	…	…	-0.24	(0.004)
Δ in immigrants	0.23	(0.054)	0.22	(0.082)
Δ in culture and heritage degree holders	-0.04	(0.713)	-0.03	(0.775)
Intercept	0.46	(0.000)	0.44	(0.000)
F	40.1		37.7	
Probability > F	0.000		0.000	
R-squared	0.63		0.64	
Number of observations	242		242	

… not applicable
Notes: All change variables are for the first period. Heteroskedasticity corrected p-values are in parentheses.
Sources: Canadian Census 1981, 1991 and 2001; United States Census 1980, 1990 and 2000.

5. Conclusion

This paper has examined the factors that contribute to differences in employment growth rates across North American cities. We placed particular emphasis on the role of scientists and engineers in the growth process. Scientists and engineers are specialized workers who are directly involved with the development and implementation of new innovations. This is consistent with structural models that link urban growth to increases in multifactor (total factor) productivity.

Our analysis suggests that the contribution of human capital to growth may rest on the underlying complementarities that result from diverse mixtures of human capital. We find significant interactions between scientists and engineers and the broader cross-section of degree holders located in cities: the latter may be the primary mechanism through which scientists and engineers contribute to the growth process. In short, scientists and engineers—the left brain of cities—matter most for growth when combined with a large and diverse pool of human capital.

This relationship between growth and diversity finds a parallel in research that examines the growth and performance of firms. Companies that excel in the marketplace are often those that develop an array of complementary business skills across a broad set of strategic areas, such as human resource management, marketing and financing (Baldwin and Gellatly 2003). If firms require a broad set of skills to be successful, it is not surprising that the same may hold for cities.

Our empirical models also suggest that amenities play a central role in shaping urban dynamics. Differences in climate (heating-degree days) and in our more generalized measure of amenities are positively associated with changes in long-run employment. Growth in cities is as much related to their quality of life as it is to productivity gains linked to human capital.

The second part of this paper examined the factors associated with the growth of scientists and engineers, a group of specialized workers that is often linked to differences in urban and industrial competitiveness. Our analysis finds a clear relationship between these specialized workers and the broader pool of human capital located in cities. Cities with large concentrations of these other-degree holders experience more robust science and engineering (S&E) growth than others, after controlling for a range of urban characteristics. These educated populations grow together, and there is some evidence that stronger growth in other-degree holders in the 1980s led to an acceleration of private sector S&E growth in the 1990s.

The strength of these effects needs to be set in context. S&E growth appears to be a stochastic process in which growth dynamics are strongly influenced by mean reversion. Cities that experience robust S&E growth in one period may experience weaker growth in the subsequent period.

An additional objective of our analysis was to learn more about how amenities—be they related to culture, climate or openness—help to attract workers with higher levels of human capital to cities. Florida's work suggests that amenities are an increasingly important factor driving the concentration of skilled workers in cities. Our findings are consistent with Florida's, in the sense that we find many of his variables to be associated with the growth of scientists and engineers. However, these associations were often inconsistent across time periods and specifications. This leads us to place less emphasis on culture, climate or openness as drivers of high tech growth and, instead, more emphasis on the complementarities that exist between scientists and engineers and other types of human capital.

Appendix A: Descriptive statistics

Descriptive statistics on our set of analysis variables are reported in Table A1.

Table A1
Descriptive statistics

	Mean	Median	Standard deviation	Minimum	Maximum
Urban growth model – Select analysis variables					
Average annual percentage growth in employment (1980 to 2000)	1.78	1.62	1.33	-2.92	6.17
Degree holders, percentage share of employment (1980)	17.7	17.1	4.8	7.5	35.5
Degree holders in S&E[1] occupations, percentage share of employment (1980)	1.54	1.33	0.90	0.17	6.81
Degree holders in culture occupations, percentage share of employment (1980)	0.61	0.56	0.31	0.04	2.08
Degree holders in other occupations, percentage share of employment (1980)	15.53	15.07	3.99	6.47	29.2
Amenities index (1980)	0.00	-0.06	0.26	-0.42	0.88
Average heating degrees per day (30 year average)	7.37	8.04	3.73	0.10	16.02
Average cooling degrees per day (30 year average)	1.91	1.35	1.53	0.00	7.09
Urban population (1980)	673,165	282,305	1,361,040	100,009	14,647,592
Industrial diversity index (1980)	78.91	80.11	16.62	11.80	136.19
Science and engineering growth models – Select analysis variables					
Average annual rate of S&E employment growth (1980 to 1990)	4.82	4.96	3.83	-8.58	18.04
Average annual rate of S&E employment growth (1990 to 2000)	4.61	4.42	3.63	-10.04	23.71
Average annual rate of S&E employment growth (1980 to 2000)	4.68	4.65	2.39	-4.81	11.90
Degree holders in S&E occupations (1980)	5,820	1,693	13,094	140	115,336
Degree holders in S&E occupations (1990)	10,032	2,817	22,867	204	199,239
Degree holders in cultural occupations (1980)	2,505	660	7,849	20	99,750
Degree holders in cultural occupations (1990)	4,051	1,002	12,392	68	150,268
Degree holders in non-science and non-cultural occupations (1980)	52,487	18,805	118,826	4,169	1,305,077
Degree holders in non-science and non-cultural occupations (1990)	79,744	25,503	182,402	4,878	1,991,651
Post secondary educators (1980)	2,039	911	3,495	40	34,995
Post secondary educators (1990)	2,767	1,269	4,654	24	42,886
Percentage share of S&E employment in non-business sector (1980)	21.31	18.42	13.22	2.32	63.48
Percentage share of S&E employment in non-business sector (1990)	22.62	20.02	13.09	2.64	80.43
Immigrant population (1980)	62,422	10,884	232,601	1,080	2,607,303
Immigrant population (1990)	98,739	16,597	375,797	576	4,001,853

1. Science and engineering.
Sources: Canadian Census 1981, 1991 and 2001; United States Census 1980, 1990 and 2000. Data on climate were obtained from Environment Canada (www.on.ec.gc.ca) and the National Oceanic and Atmospheric Administration (NOAA) (www.noaa.gov).

Correlation coefficients on variables in the urban growth model are presented in Table A2.

Table A2
Correlation coefficients – Urban growth models, select variables

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) Change in log employment (1980 to 2000)	1.000	…	…	…	…	…	…	…	…	…
(2) Log of employment share: degree holders (1980)	0.184[1]	1.000	…	…	…	…	…	…	…	…
(3) Log of employment share: degree holders in other occupations (1980)	0.189[1]	0.986[1]	1.000	…	…	…	…	…	…	…
(4) Log of employment share: degree holders in science and engineering occupations (1980)	0.040	0.678[1]	0.557[1]	1.000	…	…	…	…	…	…
(5) Log of employment share: degree holders in cultural occupations (1980)	0.179[1]	0.816[1]	0.778[1]	0.603[1]	1.000	…	…	…	…	…
(6) Amenities index	0.321[1]	0.323[1]	0.304[1]	0.213[1]	0.348[1]	1.000	…	…	…	…
(7) Log of urban population (1980)	-0.012	0.311[1]	0.277[1]	0.360[1]	0.349[1]	0.221[1]	1.000	…	…	…
(8) Industrial diversify index (1980)	0.035	0.095	0.068	0.252[1]	0.184[1]	0.133	0.433[1]	1.000	…	…
(9) Log of average heating degrees per day (30 year average)	-0.257[1]	-0.081	-0.119	0.140	0.021	-0.316[1]	-0.156	0.086	1.000	…
(10) Log of average cooling degrees per day (30 year average)	0.134	0.095	0.145	-0.150	-0.040	-0.150	0.129	-0.095	-0.68	1.000

… not applicable
1. All off-diagonal correlation coefficients are significant at the 1% level of confidence.
Sources: Canadian Census 1981 and 2001; United States Census 1980 and 2000. Data on climate were obtained from Environment Canada (www.on.ec.gc.ca) and the National Oceanic and Atmospheric Administration (NOAA) (www.noaa.gov).

Appendix B: Granger causality test: Culture and science and engineering (S&E) employment

The S&E partial adjustment models in Chapter 4 and the urban growth models in Chapter 3 share a common structure. Both posit that the observed variation in growth performance across cities depends on a set of initial conditions—factors related to the level or concentration of human capital and the presence of urban amenities, both measured at the beginning of the analysis period (typically 1980).

One advantage of this formulation is that it can be expected to alleviate the confounding effects of endogenous changes on the right-hand side of these growth equations—simply by treating these right-hand side variables as initial conditions and not as contemporaneously determined factors (whereby, for example, changes in the level of S&E employment depend on contemporaneous changes in cultural employment and vice-versa). This said, the adequacy with which this modeling strategy handles possible sources of endogeneity warrants some further discussion. Below we present some supplemental discussion on one possible source of endogeneity bias—the relationship between changes in S&E employment and cultural employment.

The partial adjustment models reported in Chapter 4 assume that S&E employment is a function of cultural employment. They assume that science workers are attracted to cities with more vibrant cultural environments, as these environments serve to enhance the range and quality of goods and services that urban markets make available to scientists and engineers and other high wage earners. However, as we describe in Footnote 14, these partial adjustment models can give rise to a biased association between science and cultural employment, if changes in cultural employment can be traced back to an initial science-based shock at some time in the past.

Definitively resolving the possible endogeneity bias associated with changes in culture employment requires the use of instruments that isolate its exogenous impact. This can be accomplished by 'deeply-lagging' the culture employment variable, or by obtaining another exogenous instrument that proxies its effect. Here we are constrained by the limitations of our database, which contains cross-sectional estimates of science and culture employment for three census years (the earliest being 1980) and does not afford us a suitable candidate variable to proxy the exogenous impact of culture. We can, however, comment on the extent to which endogeneity bias appears to hamper the observed relationship between science and culture for the analysis period under study. To assess this, we performed a Granger causality test, which links the level of S&E employment in 2000 to past levels of S&E employment in 1990 and 1980, along with past levels of all other time variant regressors included in the partial adjustment model. (All levels were expressed as logarithms).

The Granger test provides some evidence that past culture employment, evaluated separately in 1990 and 1980, is positively associated with the level of S&E employment in 2000, after controlling for past variation in other possible covariates of S&E employment (i.e., other-degree holders, postsecondary educators, immigration, and population size). The estimated elasticities on culture employment in 1990 and 1980, obtained from the unrestricted regression, are 0.18 and 0.18, respectively, and both are significant at the 5% level. The F statistic associated with the Granger test of culture on science was 9.4, which strongly rejects the null that culture does not cause science (the critical value associated with the F test is approximately 3).

Conversely, there is no evidence from the Granger test that causality also runs in the opposite direction—namely, that past variation in S&E employment, evaluated in 1990 and 1980, is associated with the level of culture employment in 2000. Both the estimated elasticities on S&E employment in 1990 and 1980, obtained from the unrestricted regression, were not significantly different from zero (these were -0.04 and 0.02, respectively). The F statistic associated with the Granger test of science on culture was 0.2, which does not reject the null that culture does not cause science.

Together, these results are consistent with the premise of the partial adjustment models reported in Chapter 4, in which the level of culture employment within a city is expected to influence the subsequent growth of its S&E workforce.

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