Exploiting States' Mistakes to Identify the Causal Impact of Higher Education on Growth

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1 Introduction

Should countries or regions invest more in higher education in order to grow faster? Recent policy reports on growth and productivity in Europe versus the United States[1], for example argue that a major cause for the relatively slow growth in Europe is its underinvestment in higher education. Pre-enlargement, the European Union invested only 1.1 percent of its total annual gross domestic product in higher education compared with 3 percent in the United States.

A key reason why investment in tertiary education may enhance growth is that such investments are likely to stimulate complementary investments in research and development, thereby fostering technological innovation. This explanation is consistent with panel data on American executives' tertiary education and their enterprises' investment in research and development. Scherer and Hue (1992), using data on 221 enterprises from 1970 to 1985, find a positive and significant correlation between executives' level of technical education and spending on research and development. Of course, this correlation is no guarantee , of causality but does suggest a possible complementarity between investments in higher education and investments in research and development. This complementarity is stressed by Romer (2000),[2] who argues that research and development subsidies that are unaccompanied by an increase in the supply of researchers or technicians will result in an increase in the relative price of highly educated labor but little increase in aggregate research and development and, therefore, little or no change in productivity growth.[3]

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[1]See for example Sapir (2003) or Camdessus (2004).

[2]The idea that there exists a complementarity between education and innovation, has already been formalized by Acemoglu (1995) and Redding (1996), although in the context of models that do not distinguish between different types of education.

[3]Romer cites recent empirical work, e.g Goolsbee (1998), who shows an important effect of

Today, the United States invests more than Europe in tertiary education and grows faster. In contrast, during the first thirty years after World War II, Europe grew faster than the United States even though it allocated most of its education budget to primary and secondary education. Similarly, the "Asian miracle" (high productivity growth in Asian countries like South Korea) is associated more with investments in primary and secondary education than with investments in higher education. How can we reconcile the evidence? Also, what should we make of Krueger and Lindahl (2001)'s finding that "[overall,] education [is] statistically significantly and positively associated with subsequent growth only for the countries with the lowest education"?

The contribution of this paper is twofold. First, we develop a multi-state endogenous growth framework that potentially explains the above puzzles.[4] Building on previous work by Acemoglu-Aghion-Zilibotti (2003), we model productivity growth as resulting from both *imitation* of frontier technology and *innovation* of technology. We posit that, while imitation mainly requires physical capital and less educated labor, innovation uses highly educated labor intensively. Moreover, workers can migrate, at a cost, towards states that pay higher wages for their skills. Thus, a person who is highly educated by a state that needs mainly to engage in imitation may migrate to a state where his skills will be used in innovation. Such migration further reduces the growth effects of a far-from-the-frontier state's investment in advanced education. In short, the closer a state is to the technological frontier at the beginning of the current period, the more important "high brow" education –that is, education oriented toward research at the frontier of technology– will be as a source of productivity growth. While we are unsure about exactly where the split between "high brow" and "low brow" education occurs, it seems safe to posit that, in the U.S. content, graduate education will be most growth-enhancing for states close to the technological frontier, while secondary education will be most growth-enhancing for states far from the frontier. (We will let the data determine where to split the intermediate levels of education, which are lower postsecondary and baccalaureate education.) The positive interaction between graduate education and proximity to the frontier is reinforced by migration because the further is a state from the frontier, the lower will be its wages for highly educated workers relative to frontier states', and the more will its highly educated workers emigrate

This model helps solve the above two puzzles. It first explains why tertiary education may be much more growth-enhancing in advanced countries like the United States or today's Europe than it is in developing countries that are engaged in technological "catch up." Second, the model solves Krueger and Lindahl's puzzle by showing that total human capital stock is not a sufficient statistic to predict growth because two states with the same total stock and the

federal R&D spending in the aircraft sector on the salary of physiscists and engineers working in that sector.

[4] The states in question can be countries, regions, provinces, or American states. The degree of migration that occurs will naturally depend on the size of the states to which the model is applied.

same distance from the technological frontier will grow at different rates if their human capital *composition* (primary, secondary, tertiary) differs.

The second contribution of the paper is empirical, namely that of providing suitable instruments for different types of education spending. A key problem with existing analyses of the relationship between education and growth is the endogeneity of states' education investments, which are explanatory variables in growth regressions. As argued persuasively by Bils and Klenow (2000), the resulting causality problem is serious. It may be that our model is correct: high brow education maximizes productivity growth for states that are close to the frontier and low brow education maximizes productivity growth for states far from the frontier. However, suppose that, for some exogenous reason, some states just have more productivity growth than others. The high growth states will end up being rich and close to the frontier. Rich states may spend more on high brow education as a luxury of sorts. In such a world, productivity growth, closeness to the frontier, and high brow education would be correlated, but education would not be *causing* growth.

If we are to identify how education contributes to growth, we need to compare states that have a similar distance to the frontier and yet choose different patterns of investment in education. For instance, it is useful to compare two far-from-the-frontier states, one of which invests greatly in high brow education and the other of which focuses its investment on low brow education. Yet, such comparisons are not entirely convincing by themselves because we are left wondering whether the two states are truly similar if they pursue different investments. We would like to be assured that their policies differ only because of "mistakes." That, we want to find occasions in which a state, for reasons that have nothing to do with its growth prospects, invests in education in a manner that deviates from its growth-maximizing policy. In short, we seek instrumental variables that predict states' tendencies to make exogenous investment mistakes.

Our instruments all depend on the detailed composition of political committees and all have the same basic logic. When he is able to do it, a politician needs to deliver "pork" or payback to his constituents in return for their support. In certain settings, a key form that payback can take is a specific education investment that is not fungible into cash. In order to deliver payback, therefore, a politician makes specific educational investments–for instance, investment in a research university–even if his state would prefer to spend (fungible) cash elsewhere. For example, our instruments for investments in research-university education are indicators for a state's number of legislators on federal appropriations committees. The appropriations committees can send "earmarked" funds to specific research universities but not to a specific set of primary, secondary, or low postsecondary schools. Therefore, in order to milk the full value out of a scarce appropriations committee seat, a legislator must focus funds on research universities. We explain below why a state's representation on the appropriations committee does not merely reflect contemporary partisan politics, for which we actually control. To instrument for other forms of postsecondary education, we examine chairmen of state legislatures' education committees and find chairman whose constituents benefit directly from additional expenditure on a postsecondary institution. For primary and secondary education, we use indicators of the progressiveness of judges on a state's supreme court. Below, we offer detailed explanations of these instruments and show that they predict investments in each type of education. Our resulting instrumental variables estimates of the effects of education on growth are much more credibly immune from endogeneity bias than are previous studies' estimates, which tend to use lagged values of current education stocks as instruments. We have particular confidence in the instruments for investment in research-oriented education, which is crucial for innovation in the U.S.

With the instruments in hand, we test our theoretical predictions using a panel data comprised of U.S. states and 26 birth cohorts (1947 to 1972). Our results indicate that high brow education has the most beneficial effect on growth in states that are close to the technology frontier. Our results also indicate that low-brow education raises growth the most in states that are far from the technology frontier. We also assess empirically the role played by migration. We do this by We measure states' investments in education (that is, their spending), the human capital they create with their investments (their local production of educated people), and the human capital they ultimately keep (their stock of educated people after migration). Comparing results across these measures, we show that migration aggravates the difference between a close-to-the-frontier state's growth-maximizing policy and a far-from-the-frontier state's growth-maximizing policy.

Our paper contributes to the existing literature on education and growth. A first strand in that literature (Lucas (1988) and Mankiw-Romer-Weil (1992)) would emphasize the accumulation of human capital as the main source of productivity growth. However, this approach cannot explain why growth has been sustained in the United States for the past four decades despite the fact that the rate of accumulation of skilled labor has decreased over the same period.[5] More fundamentally, as first pointed out by Benhabib and Spiegel (1994), the *stock* of human capital–not only the rate of accumulation of human capital–can positively affect growth. That the stock of human capital should matter for growth had been already emphasized by Nelson and Phelps (1966), who argued that a more educated labor force would imitate frontier technology faster. However, none of these papers, nor the subsequent contribution by Krueger and Lindahl (2001), distinguish as we do between types of education spending and consider the interplay between the composition of education spending and the country's distance from the technology frontier.

Most closely related to the present paper is Vandenbussche, Aghion, and Meghir (2005, hereafter "VAM"). We extend their theoretical framework in two dimensions. First, we introduce the possibility of migration of labor and thereby are able to account for some endogeneity of the size and composition of human capital stocks. Second, we introduce labor into the final good production sector, thereby adding realism to the model and migration decisions. On the empirical side, we are able to test our theoretical predictions in a more

[5]See Ha and Howitt (2005).

precise way than VAM. They exploit a cross-OECD panel data which covers 22 countries every five years between 1960 and 2000 and contains 122 observations. This relatively small dataset limits the identification power of their estimator, especially when both time and country fixed effects are included in the regression [6]. Moreover, exploiting cross-country data, VAM have to use a potentially imperfect instrument: ten-year lagged education spending.

Instead, by concentrating on data from American states, we can exploit a larger and more consistent dataset and use political instruments which are unavailable in a cross-country setting while also exploring the implications of migration of labor for the relationship between higher education, distance to technological frontier and growth. For instance, we have sufficient data to include not only state fixed effects and cohort fixed effects, but also linear time trends for the nine Census divisions (think regions) of the U.S. We can use observations on every cohort (with appropriate standard errors) or can observations on spaced data designed to minimize overlap between cohorts' educational experiences. Moreover, our instruments for the various types of education spending, which are based on the details of certain political committees, are stronger because we can condition on numerous indicators of contemporary partisan politics. And we can also instrument for the usual measure of distance to the frontier, which is based on labor's productivity, using alternative measures based on direct observation of innovation.

In its focus on U.S. states and the policies they use to raise their stock of educated people, this paper is related to Bound, Groen, Kezdi, and Turner (2004) and Strathman (1994). The first of these papers argues that there is only a weak relationship between the flow of new degrees produced in a state and the stock of educated workers living in that state. Bound *et al*'s evidence relies on primarily on variation across states, however. Such cross-state variation may be endogenous to states' demands for educated workers. We, in contrast, present evidence that relies on arguably arbitrary shocks to education spending within states. Strathman presents evidence that states with more mobile populations spend less on public higher education. This fact is consistent with the idea that high mobility states expect to attract highly-educated migrants from neighboring states. The fact is also consistent with the idea that high mobility states expect their own residents to leave, taking their human capital with them. In addition to the two papers just mentioned, this paper is related to a host of empirical studies of how universities affect innovation in the geographic area surrounding them. A very partial survey of such papers might include: Adams (2002); Andersson, Quigley, and Wilhelmsson (2004); Anselin, Varga, and Acs (1997); Fischer, Mafred, and Varga (2003); Florax (1992); Jaffe (1989); and Varga (1998).

The paper is organized as follows. We first present our model and its predictions. Next, we outline our empirical strategy for testing the model, including a description of our instrumental variables. We present a few case studies to give

[6] To retain identification power and obtain significance of their estimates, VAM choose to replace country fixed effects by six group dummies.

readers a sense of the "mechanics" by which politics generate arbitrary variation in states' investment in education. Then, we turn to systematic analysis of our panel data. We conclude with reflections on our results.

2 Model without migration

2.1 Economic environment

The economy is endowed with an exogenous stock of U units of unskilled labor and S units of skilled labor. A final good is produced competitively according to:

$$y_t = [A_t(u_{f,t}^{\beta} s_{f,t}^{1-\beta})]^{1-\alpha} x_t^{\alpha}$$

where A_t is the technological level, $u_{f,t}$ (respectively $s_{f,t}$) is the amount of unskilled (respectively skilled) labor in final good production, x_t is an intermediate good produced monopolistically and $(\alpha, \beta) \in (0,1) \times [0,1]$.

The intermediate monopolist faces an aggregate inverse demand curve

$$p_t = \alpha[A_t(u_{f,t}^{\beta} s_{f,t}^{1-\beta})]^{1-\alpha} x_t^{\alpha-1}$$

where p_t is the price of the intermediate good. Since it costs one unit of final good to produce one unit of intermediate good, profit maximization by intermediate producers leads to

$$x_t = \alpha^{-\frac{2}{1-\alpha}} A_t(u_{f,t}^{\beta} s_{f,t}^{1-\beta})$$

and total operating profit

$$\pi_t = \delta A_t(U_{f,t}^{\beta} S_{f,t}^{1-\beta})$$

where

$$\delta \equiv \frac{1-\alpha}{\alpha} \alpha^{-\frac{2}{1-\alpha}}$$

and $U_{f,t}$ (respectively $S_{f,t}$) is the total amount of unskilled (respectively skilled) labor employed in final good production.

The unskilled wage is equal to the marginal productivity of labor in the final good sector, hence

$$w_{u,t} = \zeta \beta A_t U_{f,t}^{\beta-1} S_{f,t}^{1-\beta} \tag{1}$$

Similarly,

$$w_{s,t} = \zeta(1-\beta) A_t U_{f,t}^{\beta} S_{f,t}^{-\beta}, \tag{2}$$

where

$$\zeta = (1-\alpha)\alpha^{-\frac{2\alpha}{1-\alpha}}.$$

These wages are those faced by the intermediate producer at the beginning of period $t+1$ when deciding on her demand for skilled and unskilled workers for the purpose of improving technology and thereby increasing profits.

2.2 Productivity dynamics

The dynamics of productivity during period $t+1$ is given by

$$A_{t+1} = A_t + \lambda[u^{\sigma}_{m,t+1} s^{1-\sigma}_{m,t+1} (\bar{A}_t - A_t) + \gamma u^{\phi}_{n,t+1} s^{1-\phi}_{n,t+1} A_t] \tag{3}$$

where: (i) $\bar{A}_t$ is the world productivity frontier at time t: (ii) A_t is the country's productivity at the end of period t; (iii) $u_{m,t+1}$ (respectively. $s_{m,t+1}$) is the amount of unskilled (respectively. skilled) labor input used in imitation at time t, $u_{n,t+1}$ (respectively. $s_{n,t+1}$) is the amount of unskilled (respectively. skilled) units of labor used in innovation at time t; (iv) $\gamma > 0$ measures the relative efficiency of innovation compared to imitation in generating productivity growth, and (v) $\lambda > 0$ reflects the efficiency of the overall process of technological improvement.

We make the following assumption:

Assumption A1: The elasticity of skilled labor is higher in innovation than in imitation activities, that is, $\phi < \sigma$.

It is useful to define

$$\hat{U}_t \equiv u_{m,t} + u_{n,t} \tag{4}$$

which represents total unskilled labor employed in productivity improvement and

$$\hat{S}_t \equiv s_{m,t} + s_{n,t} \tag{5}$$

which represents total unskilled labor employed in productivity improvement. The labor market equilibrium of course implies

$$\begin{aligned} \hat{U}_t &= U - U_{f,t} \\ \hat{S}_t &= S - S_{f,t} \end{aligned}$$

Solving the model consists in finding how the two types of human capital are allocated across the three tasks of production, imitation and innovation. We will proceed in two steps. First, we will analyze the allocation of human capital *within* technological improvement, i.e. analyze how human capital is allocated across imitation and innovation for a given level of $\hat{U}$ and $\hat{S}$ and at a given distance to the technological frontier. In the second stage, we will determine the allocation of human capital across production and technology improvement, i.e. determine how $(\hat{U}, \hat{S})$ depends on the total human capital endowment of the economy and its distance to the frontier.

2.3 Optimal hiring decisions by the intermediate firm

At beginning of period $t+1$, the intermediate producer chooses $(u_{m,t+1}, s_{m,t+1}, u_{n,t+1}, s_{n,t+1})$ to maximize her post-innovation profit minus the wage bill, or equivalently to maximize[7]

$$\begin{aligned} &\lambda\delta(U^{\beta}_{f,t} S^{1-\beta}_{f,t})[u^{\sigma}_{m,t+1} s^{1-\sigma}_{m,t+1} (\bar{A}_t - A_t) + \gamma u^{\phi}_{n,t+1} s^{1-\phi}_{n,t+1} A_t] \\ &-(u_{m,t+1} + u_{n,t+1}) w_{u,t} - (s_{m,t+1} + s_{n,t+1}) w_{s,t} \end{aligned}$$

[7] We assume the intermediate firm optimizes over one period only.

where $w_{u,t}$ and $w_{s,t}$ are respectively given by the equilibrium conditions (1) and (2).

Assuming an interior solution, the first-order conditions of this maximization program can be written

$$\begin{aligned} w_{u,t+1} &= \delta(U_{f,t+1}^{\beta} S_{f,t+1}^{1-\beta})\lambda\sigma u_{m,t+1}^{\sigma-1} s_{m,t+1}^{1-\sigma}(\bar{A}_t - A_t) \\ &= \delta(U_{f,t+1}^{\beta} S_{f,t+1}^{1-\beta})\lambda\phi u_{n,t+1}^{\phi-1} s_{n,t+1}^{1-\phi} A_t \end{aligned} \tag{6}$$

and

$$\begin{aligned} w_{s,t+1} &= \delta(U_{f,t+1}^{\beta} S_{f,t+1}^{1-\beta})\lambda(1-\sigma) u_{m,t+1}^{\sigma} s_{m,t+1}^{-\sigma}(\bar{A}_t - A_t) \\ &= \delta(U_{f,t+1}^{\beta} S_{f,t+1}^{1-\beta})\lambda(1-\phi) u_{n,t+1}^{\phi} s_{n,t+1}^{-\phi} A_t \end{aligned} \tag{7}$$

The two equations above immediately imply the following factor intensities in technological improvement, as shown in Appendix 1 (we drop the time subscripts):

Lemma 1 *When both imitation and innovation are performed in equilibrium, factor intensities in technology improvement are given by:*

$$\frac{u_m}{s_m} = \frac{\psi}{h(a)} \tag{8}$$

$$\frac{u_n}{s_n} = \frac{1}{h(a)} \tag{9}$$

where

$$\psi \equiv \frac{\sigma(1-\phi)}{(1-\sigma)\phi} > 1$$

and

$$a \equiv \frac{A}{\bar{A}}$$

is the proximity to the technological frontier and

$$h(a) \equiv \left(\frac{(1-\sigma)\psi^{\sigma}(1-a)}{(1-\phi)\gamma a}\right)^{\frac{1}{\sigma-\phi}}$$

is a decreasing function in a from Assumption A1.

Equations (8) and (9) imply that as a result of a reallocation effect (or Rybzcynski effect), an increase in $\hat{S}$ leads to a more than proportional expansion of innovation, i.e. the activity that employs skilled labor more intensively, and a concommitent contraction of imitation. This follows from the following facts: (i) because the elasticity of skilled labor in generating productivity growth, is higher in innovation than imitation, it is growth-enhancing for the firm to allocate the extra supply of highly educated labor to innovation rather than imitation; (ii) the inflow of skilled labor into innovation increases the marginal productivity of unskilled labor on innovation and makes it profitable for the firm to reallocate some unskilled labor from imitation to innovation; (iii) the inflow of unskilled labor from imitation to innovation, increases the marginal productivity of skilled labor on innovation further, making it profitable for the firm to reallocate skilled workers that were previously employed in imitation, into innovation.

Lemma 1 also implies

Lemma 2 *The growth rate of productivity is given by*

$$g_A/\gamma\lambda = \phi h(a)^{1-\phi}\hat{U} + (1-\phi)h(a)^{-\phi}\hat{S}$$

Proof. See Appendix 1. ■

In particular, given that $h(a)$ is decreasing in a, we see that the contribution of unskilled labor to the equilibrium growth rate, decreases with the proximity to frontier a, whereas the contribution of skilled labor increases. This follows immediately from the fact that: (i) increasing the supply of (residual) skilled labor $\hat{S}$, leads to a reallocation of skilled and unskilled labor from imitation to innovation (the Rybzcynski effect described above); (ii) that a reallocation of skilled and unskilled labor from imitation to innovation, is all the more growth-enhancing that the economy is closer to the technological frontier, so that innovation matters more relative to imitation.

As we shall see below, the positive interaction effect between $\hat{S}$ and a, that is between the supply of highly educated labor earmarked for productivity enhancing activities and the proximity to the frontier, will translate into a positive, although softened, interaction effect between a and the total supply of highly educated labor S.

2.4 Full characterization of the solution

Equations (4), (5), (8) and (9) fully characterize the allocation of human capital within technological improvement in the case of an interior solution, for a given level of human capital resources $\hat{U}$ and $\hat{S}$ employed in technology improvement. We now proceed to the determination of $\hat{U}$ and $\hat{S}$.

Taking the ratio of (1) to (2) and equating it with the ratio of (6) to (7), we immediately obtain the following result:

Lemma 3 *The factor intensity in the final production sector is:*

$$\frac{U_f}{S_f} = \frac{\Gamma}{h(a)} \tag{10}$$

where

$$\Gamma = \frac{\beta(1-\phi)}{\phi(1-\beta)}$$

Intuitively, the closer the state is to the frontier, that is the larger a, the more growth-enhancing and therefore the more expensive highly educated labor becomes, which in turn induces the firm to substitute unskilled labor for skilled labor in production.

Equating (1) to (6) and (2) to (7), one obtains a system of two linear equations in $\hat{U}$ and $\hat{S}$ which, once solved, yields parts (a) and (b) of the following lemma:

Lemma 4 *(a) In an interior solution, the total human capital allocated to productivity improvement is given by:*

$$\begin{pmatrix} \hat{U} \\ \hat{S} \end{pmatrix} = (1-\beta)\frac{U - \frac{\Gamma S}{h(a)}}{1+\alpha^{-3}} \begin{pmatrix} 1 \\ \frac{-\phi}{1-\phi}h(a) \end{pmatrix} + \frac{1}{1+\alpha^3} \begin{pmatrix} U - U^* \\ S - S^* \end{pmatrix} \tag{11}$$

where

$$\begin{pmatrix} U^* \\ S^* \end{pmatrix} = \begin{pmatrix} \frac{\Gamma S^*}{h(a)} \\ \frac{\beta h(a)^{\phi}}{\phi \Gamma \lambda \gamma}\alpha^3 \end{pmatrix}$$

(b) An interior solution obtains if and only if

$$\frac{\beta + \Gamma(1-\beta) + \alpha^{-3}}{\beta + \Gamma(1-\beta) + \Gamma\alpha^{-3}} \frac{\Gamma}{h(a)} \le \frac{(U - U^*)}{(S - S^*)} \le \frac{\beta + \Delta(1-\beta) + \alpha^{-3}}{\beta + \Delta(1-\beta) + \Delta\alpha^{-3}} \frac{\Gamma}{h(a)} \tag{12}$$

where

$$\Delta \equiv \frac{\Gamma}{\Psi} = \frac{\beta(1-\sigma)}{\sigma(1-\beta)}.$$

(c) No human capital resources are devoted to technological progress whenever

$$S < \min\left(\frac{1}{\Gamma}\left(\frac{\zeta\beta}{\delta\phi\lambda\gamma}\right)^{\frac{1}{1-\phi}} U^{-\frac{\phi}{1-\phi}}, \frac{1}{\Delta}\left(\frac{\zeta\beta}{\delta\sigma\lambda}\frac{a}{1-a}\right)^{\frac{1}{1-\sigma}} U^{-\frac{\sigma}{1-\sigma}}\right)$$

Proof. See Appendix 1. ■

The conditions for an interior solution can be better seen on Figure 1 which, for illustrative purposes, represents a case where $\Delta > 1$[8]. The dotted line (F) represents the factor intensity in final good production. Below the curve (P)-(P)[9], no technological progress takes place. Indeed there is a minimum level of human capital (U^*, S^*) required for technological progress to happen. Wages in the intermediate firm are proportional to the size of the final good market, which in turn is proportional to the total quantity of labor employed in final good production. By contrast, wages in the final good sector depend only on the ratio of skilled labor to unskilled labor in production and the level of productivity, which is always at least equal to A_t. Therefore, if the economy is poorly endowed with either type of labor, the size of the final good market

[8] Since $\Psi > 1$, we always have $\Delta < \Gamma$. In the case where $\Delta < 1 < \Gamma$, the (F) line would be between the lines (N) and (M). In the case where $\Gamma < 1$, both lines (M) and (N) would be below (F).

[9] This curve is formed of parts of two hyperbolas. These two parts meet at (U^*, S^*).

will not be large enough to attract labor in the intermediate firm. Above the line (N), which is the region violating the left inequality in (12), the economy is richly endowed in skilled human capital relative to unskilled human capital and this leads to specialization in innovation. Conversely below the line (M), which is the region violating the right inequality in (12), the economy is richly endowed in unskilled human capital relative to skilled and this leads to specialization in imitation.

When a increases, the (F) lines rotates clockwise, (U^*, S^*) slides to the right along (PP), and (M) and (N) rotate clockwise around (U^*, S^*), so that the minimum level of skilled (resp. unskilled) human capital for technological progress to happen decreases (resp. increases), which is quite intuitive since higher proximity to the frontier increases the relative importance of innovation as a source of productivity growth, and the elasticity of skilled labor is higher in innovation than in imitation.

What is the effect of an increase in the total supply of high education S on the amount of human capital resources used for technological improvement (when the solution is interior)? From (11), one sees that it has two main effects. The first one is a *growth-neutral reallocation (or recomposition) effect*, captured by the first term in (11) (that this effect be growth-neutral follows immediately from Lemma 2). Through this effect proportional to $U - \frac{\Gamma S}{h(a)}$, an increase in S affects $\hat{U}$ and $\hat{S}$ in opposite directions, and these directions depend on the sign of $U - \frac{\Gamma S}{h(a)}$. When the whole economy is relatively more intensive (resp. less intensive) in skilled human capital than the final good sector, so that $U - \frac{\Gamma S}{h(a)} < 0$ (resp. > 0), an increase in the economy's endowment in skilled human capital leads to an increase (resp. decrease) in the amount of skilled labor and a decrease (resp. increase) in the amount of unskilled labor allocated to technological improvement, and these two effects compensate each other out. The second effect is a positive *pure size effect*, captured by the second term in (11), which indicates that part of the extra endowment of skilled labor is allocated to technological improvement.

2.5 Main prediction

Substituting (11) into the expression for g_A in Lemma 2, we obtain the following proposition

Proposition 5 *The growth rate of technology in the economy is given by*

$$g_A/\gamma\lambda = \frac{\phi h(a)^{1-\phi}(U - U^*) + (1-\phi)h(a)^{-\phi}(S - S^*)}{1 + \alpha^3}$$

This immediately implies our main comparative static result:

Proposition 6 *(i)* $\frac{\partial g_A}{\partial U} > 0; (ii) \frac{\partial g_A}{\partial S} > 0; (iii) \frac{\partial^2 g_A}{\partial U \partial a} < 0; (iv) \frac{\partial^2 g_A}{\partial S \partial a} > 0.$

Proof. (i) $\frac{1}{\lambda\gamma}\frac{\partial g_A}{\partial U} = \frac{1}{1+\alpha^3}\phi h(a)^{1-\phi}$

(ii) $\frac{1}{\lambda\gamma}\frac{\partial g_A}{\partial S} = \frac{1}{1+\alpha^3}(1-\phi)h(a)^{-\phi}$

Since h is a decreasing function of a, (iii) and (iv) follow directly. ■

Thus we obtain again a Rybzcynski effect, and as a result a positive interaction between proximity to the frontier and supply of highly educated labor (this time, the total supply) although the effect is attenuated, namely

$$\begin{aligned} \frac{\partial^2}{\partial a \partial S}(g_A/\gamma\lambda) &= \frac{1}{1+\alpha^3}\frac{\partial^2}{\partial a \partial \widehat{S}}(g_A/\gamma\lambda) \\ &< \frac{\partial^2}{\partial a \partial \widehat{S}}(g_A/\gamma\lambda). \end{aligned}$$

This, in turn, results from the fact that part of the increase in the total supply of skilled labor will be absorbed by the production sector, therefore resulting in a lower increase in the supply of highly educated labor $\widehat{S}$ used by the intermediate sector for the purpose of increasing productivity. In any case, the interaction between proximity to the frontier and the supply of highly educated labor, is positive, and this is the main prediction that we shall test in our empirical analysis.

3 Introducing migration

3.1 The migration equation

Here, we extend our basic model by introducing the possibility for skilled workers to migrate to more productive states. S now represents the pre-migration stock of skilled human capital in a state. Since we do not allow migration of unskilled workers, U is both the pre-migration and post-migration stock of unskilled human capital.

The migration technology is described as follows. By spending $\mu\bar{A}_t$, a skilled worker migrates to the frontier economy with probability one at date $t+1$. The variable μ is uniformly distributed between 0 and M. A skilled worker attempts to migrate if and only if

$$(\overline{w}_{t+1} - w_{t+1}) - \mu\bar{A}_t \geq 0$$

where w_{t+1} (respectively. $\overline{w}_{t+1}$) is the (skilled) wage in the country (respectively. at the frontier). This implies that the equilibrium fraction of migrating workers is

$$\mu^*(a_t, U, S) \equiv \frac{1}{M}(\frac{\overline{w}_{t+1} - w_{t+1}}{\bar{A}_t})$$

or, replacing wages by the marginal productivity of skilled labor in innovation:

$$\mu^*(a_t, U, S) = \frac{1}{M}[\frac{\overline{w}_{t+1}}{\bar{A}_t} - \delta\lambda\gamma(1-\phi)\Gamma^\beta S_f h(a_t)^{-\beta-\phi} a_t] \tag{13}$$

Substituting S_f in the equation above, one can derive the following Proposition, as shown in Appendix 2:

Proposition 7 *(i)* $\frac{\partial \mu^*(a_t,U,S)}{\partial U} < 0$;*(ii)*$\frac{\partial \mu^*(a_t,U,S)}{\partial S} < 0$;*(iii)*$\frac{\partial \mu^*(a_t,U,S)}{\partial a} < 0$;*(iv)*$\frac{\partial^2 \mu^*(a_t,U,S)}{\partial S \partial a} < 0$

Proof. See Appendix 2 ■

3.2 The effect of higher education on growth

Using the fact that the (post migration) effective supply of skilled labor available for the intermediate good producer investing in technological improvement, is equal to $S(1-\mu^*(a_t,U,S))$, and going through the same steps as in the previous section to derive the equilibrium growth rate, we get:

Proposition 8 *When the economy is subject to skilled labor emigration, its growth rate is*

$$g_A/\gamma\lambda = \frac{\phi h(a)^{1-\phi}(U-U^*) + (1-\phi)h(a)^{-\phi}[S(1-\mu^*(a,U,S)) - S^*]}{1+\alpha^3}$$

Therefore we have:

$$\frac{\partial g_A}{\partial S} = \frac{(1-\phi)}{1+\alpha^3} h(a)^{-\phi}[(1-\mu^*(a,U,S)) - S\frac{\partial \mu^*(a_t,U,S)}{\partial S}] \tag{14}$$

which increases faster with a than in the absence of migration when

$$\frac{\partial g}{\partial S} = \frac{(1-\phi)}{1+\alpha^3} h(a)^{-\phi}.$$

Thus, allowing for migration reinforces the positive interaction between higher education spending and the proximity to the technological frontier with regards to their effects on productivity growth, that is:

Proposition 9 *(a)*

$$\frac{\partial^2 g}{\partial S \partial a} / \textit{ migration} > \frac{\partial^2 g}{\partial S \partial a} / \textit{ no migration} > 0.$$

(b)

$$\frac{\partial^3 g}{\partial S \partial a \partial M} / \textit{ migration} < 0.$$

Thus there are three complementary reasons for why an increase in the supply of higher education should affect growth more positively in states closer to the technological frontier. The first is the *reallocation effect* (or *Rybzcynski effect*) captured by the terms $h(a)^{-\phi}$ in (14) and for which we already provided an intuition in the previous section. The second is a *migration effect* captured by the term $(1-\mu^*(a,U,S))$ in that same equation, for which the intuition is more straightforward: namely, the further below the the frontier a state is, the higher the wage differential with the technological frontier, the higher the incentive for a highly educated worker to migrate towards the frontier, and therefore the less growth-enhancing it is to invest in higher education in that state. The third is a *market size effect* captured by the term $-S\frac{\partial\mu^*(a_t,U,S)}{\partial S}$. This reflects the fact that an increase in the stock of skilled human capital increases the amount of labor employed in production, which in turn increases the marginal productivity of inovation and the wage of skilled labor all the more when the state is closer to the frontier, thereby making migration all the less attractive. That the three effects reinforce each other in inducing a positive interaction between the supply of higher education and the proximity to the frontier, explains part (a) of the Proposition. Part (b) simply reflects the fact that the higher the average migration cost as measured by M, the smaller the interaction between high education and distance to frontier, as the migration effect that drives this interaction is reduced with a higher M.

4 An Empirical Strategy for Testing the Model

4.1 The Predictions We Want to Test

We want to test whether data support the model's predictions, namely that an investment in high brow education contributes more to productivity growth if a state is closer to technological frontier and *vice versa*. We can test this prediction by regressing an area's growth on its investments in high brow and low brow education, its proximity to the frontier, and the interaction between its proximity and its high brow and low brow investments. If the model is correct, high brow education should raise growth mainly in areas close to the frontier–that is, the coefficient on the interaction term should be positive. Low brow education should raise growth mainly in areas far from the frontier–that is, the coefficient on the interaction term should be negative.

In addition, the model predicts that an investment in high brow education will induce out-migration of highly educated people if the state is far from the technological frontier. We can test this prediction by seeing how much of the difference between far-from-frontier and close-to-frontier states is explained by migration. That is, suppose we have estimated the difference (between far and close states) in the effect of education on growth. If we assign people's income back to the states that educated them, regardless of where they reside when the earn the income, how much of the difference between far and close states disappears? Put another way, if we give far-from-frontier states "credit" for the income growth associated with the people they educated, do they still get much less out of investing in high brow education than close-to-frontier states do?

We use several decades worth of data from U.S. states to conduct these tests. States are the primary setters of policies on education investments in the United States, and they set policies very independently. We view states as small open economics between which workers can migrate and that vary in their distance from the technological frontier

4.2 The Essence of the Identification Problem and the Essence of the Solution

If all states optimized (myopically or non-myopically), then they would invest in different amounts of skilled labor depending on differences in their distance from the technological frontier. That is, if all states optimized, they would describe a general equilibrium that would depend only exogenous differences in their technology. In such circumstances, we could only test the model by identifying exogenous shocks to technology and then comparing the new and old equilibria. This would be, however, a difficult task. Technology shocks are difficult to observe and are likely to be correlated with omitted variables that have independent effects on educational investments and productivity. In particular, if we somehow to were observe the arrival of a *bone fide* technological shock in one state and not another, we would have to make a very convincing case that its location was random. In general, we are concerned about omitted variables that cause states simultaneously to grow fast, have high labor productivity (be close to the frontier), and invest in high brow education.

This concern motivates us to test the model by comparing states that have the same distance to the frontier but that pursue different policies about investing in education. This means that we will necessarily be looking for states that deviate from what we posit are their optimal strategies. For instance, consider two states that are both very far from the technological frontier. Suppose that the first state invests in high brow education while the second invests in low brow education. If the model is correct, then the first state is making a mistake and should consequently experience slower productivity growth than the second. Also, the first state should experience substantial out-migration of highly educated workers, who will go to states close to the technological frontier. The first state should make only slow progress toward the frontier, not only because its loses the return to its investment as its highly educated workers leave but also it has the wrong education mix for promoting imitation. So long as some states make mistakes like the one described, we will be able to identify how their marginal investments in skills affect their outcomes.

The essence of our empirical strategy will be to compare states that arrive at a certain date with similar distance to the frontier and other determinants of productivity and that nevertheless pursue contrasting policies. In part, we make such comparisons credible by introducing controls: state effects, which eliminate state characteristics that are constant over time; cohort effects, which eliminate factors experienced in common by a cohort; and linear time trends for the nine U.S. Census divisions, which eliminate regional trajectories due to, say, a shared industrial history. Put another way, we do not depend on crude comparisons among states. Rather, we depend on variation within a state over time, given events that affect the cohort nationwide, given events that affect the trajectory of its region of the U.S. However, we do not think that such controls are sufficient because they eliminate sources of difference but ultimately do not explain why similar states pursue different policies. Rather than merely assume that states' policy choices are arbitrary, we identify several instrumental variables that may cause similar states to pursue different policies regarding investment in education. To be valid, the instruments must be correlated with states' investments in education and be credibly uncorrelated with factors that affect states' productivity growth and for which we have not controlled with fixed effects, time trends, or other covariates we will discuss.

The instrumental variables we identify arise through the *details* of politics– in particular, the individual membership of certain political committees. We believe that, controlling for states' contemporary partisan politics, the membership of the committees in question is a key source of arbitrary variation in states' education investments. Put another way, we believe that the membership of the committees is a key source of states' mistakes, and it is these mistakes we wish to exploit.

4.3 Instrumental Variables for States' Investment in Skills

States do not directly educate some people and leave others unskilled. Instead, they use a variety of policies that encourage people, largely via subsidies but also via mandates and rationing, to educate themselves to various degrees. For instance, a state might invest in primary and secondary education but neglect institutions of higher education, thereby generating a population with a low but consistent level of skill. Alternatively, a state might disproportionately invest in postsecondary training that was primarily vocational in nature, producing technicians and craftsmen who are good at working with known technology but poor at inventing new technology. Yet another state might invest disproportionately in research universities, leading to a large number of scientists, engineers, doctors, and others with a high potential to invent.

We seek instrumental variables that cause states to make disproportionate investment in a certain type of education. Our proposed instrumental variables all have a similar flavor: they are based on the idea that the people who sit on key political committees will use these positions to deliver payback to their constituents and this payback may take the form of specific education investments that are in their constituents' (narrow) self-interests (as opposed to the broad interests of the society whom the committee is intended to serve).

It is important to understand that our instruments come from the details of politics, not from general political tendencies that evince themselves in partisanship. Indeed, we will control for numerous measures of contemporary partisan politics such as voting for national and state legislators. This is because contemporary partisan politics may be endogenous to a state's economic experience. For instance, in recent U.S. elections, "old industry" states have politics that are more influenced by industrial unions' opposition to unconstrained international trade. Such politics probably generate votes for the Democratic party, and one could regard such voting as endogenous to a state's economic situation including its distance to the frontier. While much of the economic situation will be absorbed by state effects, cohort effects, and regional time trends, there may still be time-changing aspects of a state's economic situation that move votes from one party to another. Our instruments work even though we control for contemporary partisan politics because–this is important–the instruments do not really depend on a state's contemporary politics but instead depend on the interaction between the political histories of various states (or various electoral districts).

4.3.1 Instrumental variables for research or frontier-level education

It may be easiest to illustrate what we mean by describing the first of our instruments. Many investments in research universities stem from federal grants. Some federal grants are distributed on a competitive basis, and these do not interest us because the competitions are likely to allocate grants on the basis of a university's record of invention, making the investments endogenous to a state's distance from the frontier. However, other federal grants are allocated by so-called "earmarks" which are nothing more than a federal law designating that certain grant shall be directed to a certain university.[10] Earmarked grants are widely perceived as a form of "pork" or payback for legislators' home states. Legislators are not capable of evaluating research proposals on the basis of merit, so the probability of that a university gets earmarked funding is only loosely related to whether the university is conducting the most advanced research –that is, closest to the frontier or most capable of overtaking the frontier. Because earmarked grants are only given to research universities (not, for instance to colleges specializing in undergraduate teaching), a legislator who deliver payback to his constituents in the form of earmarked grants tends to shifts his state's investment in education toward research and invention, even if the state would prefer that same funds were directed toward a different type of education. This is a noteworthy point. Earmarked grants are one of the key means by which a member of the U.S. House or Senate appropriations committees can direct federal funds toward his state. There are no equivalent means of narrowly directing substantial federal funds to a single state's elementary, secondary, or non-research-oriented postsecondary institutions. Federal funds for these lower levels of education are allocated mainly through formulas that apply uniformly to states. For instance, Title I, bilingual education, and Individual with Disabilities Education Act funds are allocated through formulae based on, respectively, measures of students' poverty, limited English proficiency, and disability.[11] Pell Grants and Supplemental Educational Opportunity Grants, which mainly fund postsecondary training and undergraduate education, are allocated based on students' income. In short, if a congressman or senator wants to use his membership on the appropriations committee to deliver payback to for his state, he will end up directing funds toward research-level education, even if his state would prefer to invest in low-brow skills.

As an instrument for spending on research universities, therefore, we use

[10] For more on earmarked grants to universities, see Payne [], ...

[11] Federal legislators can also direct a small amount of money to their states through state-specific programs that appear in the U.S. Department of Education's budget. However, these programs account for a trival share of spending on U.S. primary and secondary education: less than one-tenth of one percent.

indicators for the number of members that a state has on the House and Senate appropriations committees. It is important to realize that membership on these committees, which are powerful because they control spending, is not merely a function of a state's contemporary politics. Rather, a congressman or senator works his way onto these committees through a comparison of his seniority and expertise with that of the other members of his legislative house. Thus, a state's ability to put people on these committees does not merely depend on its own current politics, but also its political history, the contemporary politics of other states, and the political histories of other states. From our point of view, there is substantial, useful arbitrariness in the make-up of the appropriations committees.

We have a high degree of confidence in our instruments based on the federal appropriations committees not only because of our own reading of the evidence but also because a number of experts on federal funding have also found substantial evidence for arbitrariness in the makeup of the appropriations committees and for connections between the committees and grants to research universities (Payne, 2001; Feller, 2002).

We narrate a few examples of these connections in our case studies, below. For now, examine Figure 2, which illustrates the connection between appropriations committee membership and federal spending in a simple way. We construct Figure 1 using our panel data, which is described more below. For now, observe that the vertical axis records spending on research universities per person (in 2004 dollars) while the horizontal axis records the number of members on the U.S. House appropriations committee. Each observation is a particular cohort in a particular state. Observe that both the spending and membership variables shown are actually residuals where state effects, cohort effects, and Census division time trends have already been partialled out. Thus, the relationship shown is above and beyond patterns whereby certain states are routinely powerful politically or whereby certain states' political power is gradually increasing.

Figure 2 Here

The figure shows that, when–given its state–a cohort has an unusually high degree of membership on the House appropriations committee, spending on research universities rises during the period the cohort would be in graduate school. Conversely, an unusually low degree of membership on the appropriations committee is associated with unusually low spending on research universities for the cohort in question. (We explain how we align cohorts with time calendar years below.)

In our formal analysis, we go further to ensure that the appropriations committee membership variables do not reflect contemporary state partisan politics. We do this by controlling for four measures of how a state's residents have voted in the most recent elections for the U.S. president and for Congress.

4.3.2 Instrumental variables for vocational postsecondary education and undergraduate education

In contrast to research universities, which receive significant funds from the federal budget, most postsecondary institutions that focus on undergraduate teaching receive whatever government support they receive from state budgets. For instance, most public universities and four-year colleges are individual line items (that is, they are funding categories) in their state's education budget. Community colleges may show up as line items, but they also show up as systems ("the Tri-County Technical College System," for instance) in their state's education budget   Grants to such postsecondary institutions are mainly for subsidizing tuition, for buildings, and for paying faculty. For our purposes, we care mainly about the fact that the state legislator who chairs his chamber's education committee can direct funds both toward postsecondary institutions in general (as opposed to primary and secondary education) and toward the specific institutions that most benefit his constituents. Thus, we suspect that if a state college happens to sit in the district that the Education Committee chairman represents, he is likely to direct funds to that college (or to colleges of that ilk, since obvious favoritism toward a single college may be frowned upon). Local businessmen are often key constituents for a state legislator because they provide key campaign financing, so we suspect that an Education Committee chairman may listen to his local business leaders when deciding which level of education to favor. If his local business leaders bemoan the dearth of technical and vocational workers, the chairman may favor lower postsecondary education (vocational and technical schools, community colleges). If they bemoan the dearth of college graduates, the chairman may favor four-year colleges. And so on.

In short, to generate instruments for state spending on a variety of educational institutions, we identify the chairman of each state's Education Committee and link the individual with the characteristics of the area he represents. While we could potentially use a wide variety of area characteristics as instrumental variables, we focus on the presence of postsecondary institutions in his area (specifically, enrollment in four-year colleges and enrollment in two-year/vocational institutions in his area) and on local industry composition (the share of employment in manufacturing, service industries, and finance, insurance, and real estate–industries that require highly educated labor). Our focus is based on our *a priori* understanding of the factors most likely to sway a state legislator toward specific educational priorities, as opposed to a generalized interest in education.[12]

We are fairly confident about our instrumental variables based on Educa-

[12] A variety of other area characteristics are nevertheless available, and it is likely that arguments could made for several others as instruments. We stayed away from characteristics that were likely to reflect contemporary politics–most obviously the area's partisanship.

Because socio-demographic information is not coded for the districts of state legislators, we associate chairmen with the three-digit zipcode area in which they live. This is a reasonable area to use because it generally overstates the size of a district in a state's lower house but understates the size of a district in a state's upper house.

tion Committee chairman because seniority and similar factors are the primary reasons why a certain legislator becomes chairman. There is no guarantee that his priorities are aligned with those of the state overall, as regards education policy. Yet, he is typically powerful enough to push funds in the direction of his preferred educational institutions.

We attempt to ensure that the variables based on the education chairman do not reflect contemporary partisan politics by controlling for the party makeup of the lower and upper house in the state. Also, we use socio-demographic characteristics from only one Census (1970) so that the chairman's district characteristics change only with the chairman, not with the socio-demographics of the state, which could be endogenous to the state's education policy. Notice that, as a result, our including state effects matters. If, for instance, the state university were consistently able to get the chairmanship for its local representative or senator, the characteristics of the chairman's area would be constant and would be absorbed by the state effects. Our instruments depend solely on variation in chairmens' areas over time within a state, for a given partisan political situation.

4.3.3 Instrumental variables for primary and secondary school spending

State courts have a major influence on both the level and distribution of primary and secondary school spending. This is because, especially from the 1950s onwards, lawsuits that invoke state constitutions' clauses about support for educational have been used by plaintiffs interested in altering spending in public primary and secondary schools. More than 80 percent of public spending on primary and secondary schools is now controlled, directly or indirectly, by a states' systems of school finance, which are greatly affected by state courts' ruling on the lawsuits. From our point of view, the lawsuits generate useful, arbitrary variation in spending on primary and secondary public education. This is because the preferences of the individual judges who try the lawsuits can have an important effect but there is a fair amount of arbitrariness in the assignment of judges to the cases. State supreme court judges, who most often decide the cases, are appointed or elected to long terms. Their preferences are thus often poorly aligned with or largely immune from contemporary politics (this is why state legislators often complain about judicial activism). Moreover, because school finance cases require extraordinary time commitments, particularly in the findings stage, many states try part or all of their school finance cases with only a subset of the judges on the court. An individual judge's assignment to the case will depend on whether he is committed to another time-consuming case at the time when a school finance case arrives. In short, we are confident that the makeup of a state's supreme court can affect the outcome of a school finance case and yet will not merely reflect contemporary politics.

The stereotype is that progressive judges favor higher spending for public elementary and secondary education. Thus, we attempt to measure the progressiveness of the judges on a state's supreme court. For judges who are elected, we use their party affiliation. For judges who are appointed by a governor, we use the party affiliation who the governor who made the judge's initial appointment. In the "Solid South" (the area of the Confederacy where few judges were registered Republicans for many years), we use measures from judges' profiles that are designed to pick up the differences between progressives and non-progressives.

The specific variables we use as instruments are the percentage of judges on the state's supreme court who are progressives and an indicator for whether the chief justice is a progressive. We simultaneously control for the partisan make-up of the state's lower and upper legislative houses in order to ensure that the instruments do not merely reflect contemporary state politics.

Of all our instruments, these instruments based on state supreme courts are the least satisfactory. This is not because there is insufficient arbitrariness in the preferences of judges who try school finance cases. We are confident that there is sufficient arbitrariness. Rather, it is because there is only a weak relationship between judges' preferences and outcomes in elementary and secondary education. The relationship is weak for several reasons. First, school finance is poorly understand because the economics of property taxation are complicated and because school finance plans are typically written in an obfuscatory way. Judges and politicians have never been able to see through the intricacies of property taxes and price capitalization to observe which plans indirectly impose a high marginal tax rate that shrinks the pie of total resources much more than a low marginal tax rate plan would. As a result, courts and legislators are frequently bewildered to find that their school finance plans produce effects they did not expect. Among judges who attempt to achieve similar outcomes, some unintentionally level down (make spending more equal but at a lower level) while others level up (Hoxby, 2001).

Second, school finance is one of the largest and most salient areas of expenditure and taxation for most states. As a result, even very influential judges are only one of the factors that affect school spending. Their preferences control a smaller share of the total within-state variation in elementary and secondary spending then do the preferences of individuals with regard to postsecondary education. Third, although there are stereotypes about progressiveness and the level of school spending, most progressives do not claim to raise average school spending but instead claim to redistribute spending to promote equal educational opportunities. But it is not even clear what this means. The same increase in spending could be dedicated to promoting literacy and numeracy for all or dedicated to making advanced curricula available to gifted students from disadvantaged backgrounds. Without micro-data on the distribution of spending, it is unclear whether we should expect better high school diploma holders or more students engaged in doctoral study. (Micro-data on public school spending is not available for most of our cohorts.) Finally, it has long been observed that there is only a tenuous empirical relationship between education outcomes and school spending at the elementary and secondary level. There are myriad explanations for this stylized fact, but they are beyond the scope of this paper. Suffice it to say that even when a judge does succeed in generating the spending he intends, the spending may not translate into substantially different educational outcomes.

4.4 Instrumenting for proximity to the frontier

Thus far, we have not discussed concerns about whether a state's proximity to the frontier is endogenous. In practice, proximity to the frontier is a slow-changing variable simple because a state's technology cannot be replaced overnight. We are not, therefore, overly concerned about *true* proximity jumping when an event occurs that boost education investment and growth within a state, in the short-term, relative to the trend in the region. Indeed, if this were our concern, we could instrument for proximity with lagged measures of itself, as previous authors have done.

Our concern about proximity is, rather, that the data that contribute to our measure of growth also contribute to our measure of distance to the frontier. While we do not actually use the same data series for both (our measure of growth is based on gross state product per worker; our measure of proximity to the frontier is personal income–labor's product–per worker), some of the same data is used in the construction of the two series. If there are errors in those data, the errors will be propagated across our measures of growth and proximity to the frontier. Measurement error that occurs in a dependent variable and an explanatory variable can generate spurious correlation that confuses true relationships.

A standard remedy for such problems is instrumenting for the explanatory variable in question with an alternative measure of the same true variable that could not share the same sources of measurement error. In this case, we seek an alternative measure of a state's true proximity from the technological frontier. Patents are just such a measure. If a state is producing numerous patents for inventions (called "utility patents"), it is likely to be at the technological frontier because new technologies are constantly being refined and innovated upon while old technologies are too well known to produce such activity.[13] Yet, the recording of patents has nothing to do with measuring labor's product, so any correlation between patents and distance to the frontier is due to their true correlation, not the propagation of measurement error.

In fact, a state's patenting activity is strongly correlated with its distance to the frontier, and this remains true when we control for state effects, cohort effects, and linear time trends for each Census division. We instrument for distance to the frontier with a cubic in patents, and we are confident that this procedure eliminates correlated measurement error.[14]

[13] We record utility or inventive patents rather than defensive patents, which are generated when the holder of an established technology fends off a prospective imitator who is wants to patent existing technology. The vast majority of patents are utility patents.

[14] The distribution of patents is highly right-skewed and suggests that they grow exponentially at least. Thus, we actually estimate a cubic on ln(patents). Put another way, if a state's proximity to the technological frontier were a *linear* function of its number of patents,

We describe the patents and all of our other instrumental variables more exactly in our data appendix.

5 Politics, proximity to the frontier, and growth: three case studies

In this section, we narrate three cases in which members of the federal appropriations committees used their influence to "pay back" their states through increased funding for research-type education. We do this to give readers some sense of how the process actually works–how politicians boost spending on their state's research institutions to "cultivate a favorable image among grateful constituents" (Greenberg, 2001). In particular, we illustrate the relevance of committee membership to the allocation of federal funding, the arbitrariness of the funding vis-a-vis a state's growth and proximity to the frontier, and the consequences of the arbitrary funding.

The three cases we consider concern two far-from-frontier states, namely Alabama in the 1960s and West Virginia in the late 1980s, and a close-to-frontier state, namely Massachusetts in the late 1970s. In each of these cases, a congressmen or senator being on a U.S. appropriations committee led to an infusion of federal research funding over and above the amount allocated to states with similar geography and technology. We show that payback in this form generally led to increased numbers of degrees of a high-brow type. However, we find no evidence that the payback generated increased growth in the two far-from-frontier states, nor do we observe a prior increase in these states' proximity to the technological frontier that might have justified the increase in funding (if we reason in terms of our model). In contrast, we find that Massachusetts did experience increased growth that coincides with its member on the House Appropriations Committee generating an infusion of federal funding.

5.1 Alabama

The history of science funding in Alabama is closely associated with the name of Lister Hill, who represented that state in the Senate from 1938 until 1969. Hill served as a member of the Senate's Appropriation Committee from the early 1950s until 1967. Using his influence on the committee, Hill managed to secure a large federal grant in 1966 for the Alabama Regional Medical Program. This grant helped finance the Lister Hill Library building, along with new facilities for the Schools of Nursing and Medicine at the University of Alabama-Birmingham.

Unlike research grants, which are usually spread over time, the money from Hill's grant appears to have been disbursed in a single federal budget cycle. Figure 3 depicts the evolution of federal spending for university research in $1000 per capita in Alabama and two comparison states, Mississippi and Georgia, in

close-to-frontier states would be too far apart and would shift their positions too dramatically for plausibility.

the 1950s and 1960s.[15] The three states are geographically close. Also, Alabama and Mississippi had similar patterns of education attainment prior to the Hill grants, and Alabama and Georgia had very similar proximity to the frontier before the Hill grants.

Figure 3 shows that Alabama's funding tracks that for the other two states, except in 1967 where total funding for Alabama almost doubles. Alabama's funding returns immediately to trend in 1968, when Lister Hill leaves the Appropriation Committee.

FIGURE 3 HERE

Figure 4 shows the share of age cohorts born in Alabama and Mississippi with professional degrees.[16] We focus on professional degrees because medical degrees are a type of professional degree, and Hill mainly endowed medical research. The calendar year in the x-axis refer to the year that each cohort turned 18.[17] The vertical lines in these graphs, and throughout the section, refer to the first cohort to have spent their entire college or graduate school years in a post-grant regime.

In the Alabama case, the post-Lister Hill cohorts turned 18 in 1963 (they were 22 in 1967, in time to enter graduate programs). The trends in Alabama and Mississippi look similar before the Hill grants, but the post-Hill cohorts do indeed appear to be getting an increased number of medical degrees. Indeed, professional degrees in Alabama overtake professional degrees in Mississippi in the years immediately following the Hill grant.

FIGURES 4, 5, and 6 HERE

We turn next to the effect of this federal funding on Alabama's economy. Our labor productivity-based measure of proximity to the frontier is unavailable for the 1960s, so we use one based on patent data. In Figure 5, we show the Alabama's proximity to the frontier was similar to Georgia's before the Hill grant.[18] Instead of Alabama's proximity rising relative to Georgia's after the

[15] The data underlying this graph are taken from two different sources. The 1950s data are from the Biennial Survey of Education's statistics of Higher Education. The 1960s data are from a National Science Foundation publication, "Federal Support to Universities and Colleges." Data for the years 1959-1962 are missing, and we interpolated between the series for ease of presentation. There is no guarantee that the data were collected in a consistent manner from one decade to the next and no clear way to match the two series. However, we do not think that this would affect the comparison between Alabama and Mississippi or Georgia because the three states continue to mirror each other after 1963.

[16] Professional degrees include those for medicine, dentistry, chiropractic, optometry, osteopathic medicine, pharmacy, podiatry, veterinary medicine, law, and theology.

[17] Educational attainment is measured for state-age cohorts in the 1990 and 2000, and are based on an individual's state of birth. For the oldest cohorts (those aged 18 in 1945-54), we only use data from the 1990 census, when these individuals would have been 54-63 years of age. The rest of the shares are based on merged data from the 1990 and 2000 Censuses. We assume that a cohort's educational attainment is fixed from age 27 on.

[18] We scale the ranking to fall between zero and one. We use Georgia rather than Mississippi as a point of comparison because Mississippi's patents per capita are always far below Georgia's and Alabama's and thus make the evolution in Alabama difficult to see.

Hill grants, Alabama's proximity first stays flat and then falls, while Georgia's proximity rises substantially through 2000. In short, we cannot explain the Hill grants by better technology in Alabama prior the Hill grant, not did the grant generate any apparent boost to technology in Alabama.

In Figure 6, we examine real economic growth per employee in Alabama, Georgia, and Mississippi. The relevant year to begin looking for a trend break due to the Hill grants is 1972, the first year that students educated at the new University of Alabama facilities could have entered the labor force. We see no evidence that Alabama began systematically to grow faster than its neighbors after 1972. In fact, its growth looks very similar to theirs.

5.2 West Virginia

Senator Robert Byrd (Democrat, West Virginia) was appointed to the Appropriation Committee in 1958. When the Democrats regained control of the Senate in 1988, Byrd became chair of the committee. With his help, the University of West Virginia became the 4th largest recipient of earmarked grants over the decade (Savage, 1999). Byrd still sits on the committee today, although he is the ranking minority member (the Democrats no longer being in control of the Senate). Figure 7 shows federal appropriations to universities for research in West Virginia and two comparison states, Kentucky and Arkansas. These three states are not only geographically proximate; they are also traditionally similar in proximity to the technological frontier, usually in the most distant third of states.

FIGURE 7 HERE

The trend break in federal funding to West Virginia with the appointment of Robert Byrd is quite obvious in Figure 7: West Virginia and Kentucky have nearly identical series until 1988, at which point West Virginia pulls away from the pack for the next six to eight years.

Figure 8 shows research degree completion in West Virginia before and after Byrd's chairmanship of the Appropriations Committee. One could argue that there is a small increase, but West Virginia's number of research degrees was so small initially that graphical evidence is not terribly helpful. We revisit the question in our systematic analysis. Figures 9 and 10 show, respectively, West Virginia's proximity to the frontier and West Virginia's growth. In both cases, we see no evidence that West Virginia enjoys better performance than Kentucky and Arkansas after it receives Byrd's infusion of funding.

FIGURE 8, 9, 10 HERE

5.3 Massachusetts

Silvio Conte (Republican, Massachusetts) was a member of the House of Representatives and of the House Appropriations Committee from 1959 until his death in 1991. He was appointed as the ranking Republican member on the

Committee in 1978, the top position held by a member of the minority party. He also served as the ranking member on the Labor, Health and Human Services and Education Subcommittee. While Conte was a self-styled anti-pork crusader, even going so far as to don a pig mask to denounce a proposed water project in North Dakota, he brought home a substantial and sustained amount of federal funding for higher education to his state. Boston University renamed a center in his honor in 1985 in gratitude for his help in funding biomedical research and medical education. Among other grants, Conte secured $15 million for the Polymer Research Center at the University of Massachusetts and even a $2 million grant for Smith, a small women's college in his district.[19] We shall focus on comparisons between Massachusetts and California because they are two of the states that were closest to the frontier before Conte's grants.

Figure 11 shows that federal research funding (in $1000 per capita) was already higher in Massachusetts than in California in the 1970s, but prior to 1978 the trend is flat in both states. After the appointment of Conte to ranking member in 1978, funding climbs steadily in Massachusetts relative to California.

FIGURE 11 HERE

We next turn to a comparison between Massachusetts and California in terms of professional degrees. We focus on professional degrees because, like Lister Hill, Silvio Conte focused on grants for medical research and health sciences. (There are research centers are named for both Hill and Conte at the National Institutes of Health). Figure 12 shows that Massachusetts' medical degrees clearly increase relative to those in California after Conte's grants.

FIGURE 12 HERE

Interestingly, unlike the previous two case studies that involved far-from-frontier states, the Conte-induced shock to research funding in Massachusetts does appear to have translated into productivity gains for Massachusetts.

Figure 13 shows that Massachusetts was substantially further from the frontier than California prior to the Conte shock, but the two proximity series evolve in parallel fashion prior to the early 1980s. However, soon after Conte's grants began, Massachusetts began quickly moving closer to the technology frontier. It had largely caught up to California within 15 years. Figure 14 shows that, beginning in the year that the first post-Conte graduates would have entered the labor market, Massachusetts also began outpacing California in economic growth. The period of rapid growth, sometimes called the "Massachusetts Miracle," lasted for about a decade and is associated with the expansion of biotech and high-tech industries in the Boston metropolitan area. We hesitate to attribute all of Massachusetts' growth to university funding in general or to Conte's political power in particular. Nevertheless, there is a striking contrast between the post-grant increase in Massachusetts' growth and the absence of post-grant increases in growth in Alabama and West Virginia.

[19] Details of Conte's career were gathered from the website for Silvio O. Conte's congressional papers at the University of Massachusetts-Amherst. The link is: <http://www.library.umass.edu/spcoll/manuscripts/conte_papers/silvio.html>.

FIGURES 13 AND 14 HERE

Overall, the case studies support the predictions of our model. They give us the confidence to test the model more systematically using data on many states and many cohorts.

6 Data and Measurement

The data we use to construct our panel are so myriad that we must relegate many details to the data appendix. In this section, we merely explain the key measurement issues.

Our panel is based on birth cohorts and states. We start with the 1947 birth cohort because data quality or availability for a number of variables drops off for prior cohorts. We end with the 1972 birth cohort because we want to give people time to participate in the labor force and that cohort is only 33 years of age even in 2005. We include the 48 continental United States. We do not include the District of Columbia as a "state" because it is too integrated with Maryland (on the one side) and Virginia (on the other) to be considered a small open economy. We do not include Alaska and Hawaii for reasons of data quality for our early birth cohorts. The panel thus has 1248 observations (48 states times 26 cohorts). Descriptive statistics for the dataset are shown in Appendix Table 1.

6.1 Measuring Education Investments

There are two basic approaches to measuring the education investments made in each cohort. The first is based on spending on education (investment). The second is based on educational attainment (the stock of education).

First, we measure a state's investment in a cohort's education simply by recording the spending associated with each school-year in which the cohort should have been educated. For instance, consider people in the 1947 birth cohort. They would normally enter kindergarten in 1952 (age 5), enter first grade in 1953, and so on–entering twelfth grade in 1964. If they continue to postsecondary education, they could begin a freshman year in 1975 and begin a post-baccalaureate, graduate program in 1979. Of course, not all students advance in school at a regular pace, but we want to measure the cohort's educational *opportunities*. To do this, we simply add up the total spent on each grade of education in the year in question and divide by the size of the cohort over whom the spending was spread. The former variable comes from administrative (school) data; the latter variable comes from population by single-year-of-age estimates based on Census and related data. Note that we divide by the cohort size, not by the number of people who actually enroll in the grade in question. This is because enrollment is endogenous to the opportunities offered.

The spending-based measure of education investment has many good points. It is quite accurately measured. It incorporates the difference in the cost of various levels of education. That is, a year of education for a doctoral student in chemistry costs more than a year of kindergarten. Such cost differences ought to be noted because states allocate real budgets. Most importantly, the spending-based measure records what state policy actually affects: spending. People can refuse to take up educational opportunities when they are offered, and people may be particularly likely to ignore opportunities if they are poorly aligned with demand for workers in the state. For instance, a person might ignore an opportunity to get a high brow education offered by his far-from-the-frontier state if he dislikes the idea of moving to a close-to-the-frontier state, where most of jobs for such workers may be located.

Second, we measure a state's investment in a cohort's education by recording the cohort's educational attainment. This is the parallel of recording a firm's assets and backing out the implied investments. We can measure a cohort's attainment once it has a reached an adult age (26) at which few of its members continue to enroll in school. Using 1990 and 2000 Census data, we record each adult's educational attainment and associate him with the state in which he was born. Of course, people may be educated in states other the one where they were born, but state of birth is best available indicator of the state where older adults were educated. Also, unlike state of education, state of birth is likely to reflect *opportunities* and is unlikely to reflect people self-selecting into states based on their educational policies.

The attainment-based measure of education investment is useful for two reasons. First, it allows us to see whether states systematically differ in the degree to which spending is converted into educational attainment. It would not be surprising if, for instance, far-from-the-frontier states have difficulty producing as many high brow degree recipients per dollar spent on high brow education as close-to-the-frontier states do. Second, we can observe migration because we record not only a person's state of birth but also their state of residence. For example, we can see what happens when a far-from-the-frontier state produces numerous people with high brow degrees. Do they stay or do they migrate to a state close to the frontier?

6.2 The Timing of the Instruments

In general, the instrumental variables for a cohort are measured in such a way that they correspond to the years in which the cohort was supposed to get education of the relevant type. Thus, the federal appropriations committee variables should be measured for the years in which the cohort could be in graduate education; the variables based on the state education chairman should be measured for the years in which the cohort could be in two-year college and in four-year college; and variables based on state supreme courts should be measured for the years in which the cohort could be in kindergarten through grade twelve.

The only question that arises is how much of a lag to leave between a committee member's being able to exert influence and actual appropriations arriving in the educational institutions. Many politicians in the United States are on a two-year cycle and presumably need to be able to show something for their efforts at the end of two years. Thus, we believe on *a priori* grounds that two years is a reasonable lag. For instance, if an education committee chairman is going to show the college in his district that he can direct funds toward it, we think that he will try to do it within two years of being made the chairman. It is obvious, given the reality of budgeting, that a lag of zero would be too short. Four years is also implausible because a four year lag would mean that the vast majority of politicians in the U.S. would be unable to deliver any payback before facing a reelection campaign. As an empirical matter, we find little difference between the remaining plausible candidates for the lag: one year, two years, and three years. Therefore, we settle on a two year lag as being most plausible and also centered within the range of plausible lags.

Note that the controls for partisan politics, which are designed to partial out variation in instruments associated with contemporary politics, are recorded with timing identical to that of the instruments. For instance, if we measure federal appropriations membership for the years from 1972 to 1975 (to correspond with a cohort's period of opportunities for graduate study), we also measure voting for federal offices (U.S. president and congressmen) for the years from 1972 to 1975.

6.3 Proximity to the frontier

Our measure of proximity to the frontier is fairly standard. We measure labor's product per employee in a state, and we divide that measure of labor productivity by the maximum labor productivity observed in any state in that year. Thus, the state with the maximum labor productivity is at the frontier and has a proximity equal to one. States that are far from the frontier tend have proximity between 0.35 and 0.5–that is, labor productivity between one third and one half of the labor productivity in the frontier state. Given the long series of data we need, the best available measure of labor's product is personal income in the state. Personal income and employment are both available at the state level for many years, measured consistently.

An alternative measure of proximity to the frontier can be based on patents, and we in fact use patents to form instruments for the productivity-based measure of proximity. It is comforting that states that are recorded as close-to-the-frontier on the basis of their labor productivity tend also to be recorded as close-to-the-frontier on the basis of their patents. This is, of course, why the instrumental variables procedure works.[20]

We associate a cohort with the distance to the frontier that the cohort faces when we have given it all of its opportunities for education and it should be entering the labor force. Put another way, when a person makes decisions about whether to continue in school, he ought to think about the distance to the frontier that he will face when he completes school, enters the labor force,

[20] It is worth noting, however, that the high degree of right skewness in the distribution of patents means that they do not naturally generate a measure of proximity to the frontier that is distributed a lot like the productivity-based measure.

and has to choose a job in which he will innovate or imitate technology. We declare the year of labor force entry to be the one in which a person is age 26 because the we have already associated the final year of graduate education opportunities with age 25.

6.4 Growth

Our measure of the economic growth associated with a cohort is the annual rate of growth in gross state product in the first decade of the cohort's influence on the labor force. That is, we want to focus on the key period during which the cohort changes the composition of the existing labor force and contributes either by innovating (those who have received a research-type education) or imitating (for those who have received a low brow education). Keep in mind that we are trying to measure a cohort's main *opportunity* to influencing the labor force and affect growth. Since we have already declared the year of labor force entry to occur at age 26, we declare that the first decade of a cohort's influence occurs from age 26 to age 35, inclusive.

The model suggests that some of the economic growth associated with highly educated workers will benefit the state into which they migrate, not the state that educated them. To investigate this, we first try giving a state's birth cohort credit for only the economic growth that takes place inside the state during the relevant decade. We then give a state's birth cohort credit for the economic growth associated with them even if they live outside the state during the relevant decade. In other words, we first allow for the actual migration that occurred, which we predict will exacerbate differences between the growth experiences of far-from-frontier and close-to-frontier states. We then un-do the actual migration that occurred by reassociating people and their income growth with their state of birth. We predict that, once we have un-done migration, some of the differences in the growth experiences of far-from-frontier and close-to-frontier states will disappear.

In short, by recording gross state product two ways, with and without migration, we hope to determine how much of a role migration plays in endogenous growth relative to the role played by innovation-enhancing and imitation-enhancing human capital.

7 Formal empirical analysis

We now turn to formal econometric analysis, estimating the equation we described above in words, namely:

$$\begin{gathered} g_{jc} = \kappa_0 + \kappa_1 S_{jc} + \kappa_2 U_{jc} + \kappa_3 S_{jc} \cdot\ a_{jc} + \kappa_4 U_{jc} \cdot \\ a_{jc} + \kappa_5 a_{jc} + \mathbf{X}_{jc} \boldsymbol{\kappa}_6 + \mathbf{I}_j \boldsymbol{\kappa}_7 + \mathbf{I}_c \boldsymbol{\kappa}_8 + \mathbf{I}_d \cdot c \boldsymbol{\kappa}_9 + \varepsilon_{jc}, \end{gathered}$$

where j indexes states, c indexes cohorts, and d indexes census divisions.

In the estimating equation, $\kappa_1 + \kappa_3$ and $\kappa_2 + \kappa_4$ reflect the effect on growth (g_{jt}) of investments in, respectively, high brow education (S_{jt}) and low brow education (U_{jt}) in a state that is at the the technological frontier (literally, where $a_{jt} = 1$). κ_1 and κ_2 reflect the effect on growth of investments in, respectively, high brow education and low brow education in a state that is infinitely far from the technological frontier (literally, where $a_{jt} = 0$). Of course, states are never in fact infinitely far from the frontier, so we use κ_1 and κ_2 simply to compute growth effects for realistic far-from-the-frontier states where a_{jt} is, say, 0.25.

In the estimating equation, $\mathbf{X}_{jt}$ is the set of political variables for which we control to make our instrumental variables more credible. That is, $\mathbf{X}_{jt}$ ensures that our instrumental variables only need to be valid conditional on contemporary politics. $\boldsymbol{\kappa}_7$ is a set of state fixed effects. $\boldsymbol{\kappa}_8$ is a set of cohort fixed effects. $\boldsymbol{\kappa}_9$ is a set of Census division-specific linear time (cohort) trends. It is worth noting here that the reason we use division-specific linear time trends rather than state-specific linear time trends is that the latter would over-control. That is, if we removed a time trend for each state, we would eliminate not only suspect variation but also much of the useful variation in states' educational policies and growth.

Although we have written the estimating equation with two levels of education to correspond with the model, we are unsure where the split between innovation-prone and imitation-prone education actually occurs in the U.S. context. Therefore, we will let the data choose the split among the four education levels we use: research type (includes professional and doctoral programs), four-year college type (includes masters degree programs), two-year college type (all lower postsecondary programs), and primary and secondary type.

We estimate four variants of the equation, which allow us to perform several tests. These variants are as follows.

Education investments measured by spending, economic growth associated with the state where it actually occurs. These estimates allow for the maximum difference between close-to- and far-from-the-frontier states because they allow the conversion of spending into education to vary among states and they also allow for the effects of migration.

Education investments measured by spending, economic growth apportioned to states based on where people were born (educated). These estimates allow the conversion of spending into education to vary among states but they un-do the effects of migration. Compared to the previous variant, we have shut down an important channel of the model so–if we reason in terms of the model–we expect to see a smaller difference between close-to- and far-from-the-frontier states.

Education investments measured by educational attainment, economic growth associated with the state where it actually occurs. These estimates assume that spending on education is converted into the same educational attainments in all states, but they do allow for the effects of migration. Relative to the first variant, we have shut down a (possibly quite minor) channel of the model so–if we reason in terms of the model–we expect to see a smaller difference between close-to and from-from-the-frontier states.

Education investments measured by educational attainment, economic growth apportioned to states based on where people were born (educated). Because these estimates assume that spending is converted into the same attainment everywhere and also un-do the effects of migration, we have shut down two channels of the models. If we reason in terms of the model, we expect to see the smallest difference between close-to and far-from-the-frontier states.

By estimating the four variants, we can get some sense of the relative importance of the reallocation (Rybzcynski) effect, the direct migration effect, and indirect effects on skill acquisition.

We estimate each of the above variants by instrumental variables in which we instrument for only the education variables and by instrumental variables in which we instrument for proximity to the frontier as well as for the education variables. The second specification is our preferred one. We show the first specification to facilitate comparison with the previous literature. We estimated but generally do not show ordinary least squares results because it is implausible that they represent causal effects. However, we describe some ordinary least estimates, purely for comparison with the instrumental variables estimates.

Because the implied first-stage equations help to reveal the role of migration, we show estimates from the implied first-stage equations as well as estimates from our main equation of interest.

7.1 First-stage equations

Tables 1 and 2 show estimates from the first-stage equations that are implied by our instrumental variables estimates. That is, they show how our political committee variables generate variation in education spending and educational attainment, even when we control for contemporary partisan politics, state effects, cohort effects, and regional time trends. We present only the coefficients of interest. Moreover, we have been deliberately parsimonious with our instruments to facilitate interpretation of the coefficients. We have available many more potential instruments based on characteristics of the federal appropriations committees, the areas that state education chairmen represent, and the characteristics of state supreme court justices.[21]

[21] There is a trade-off between parsimony and power in our first-stage equations. As a purely econometric matter, we should use every instrument available that has explanatory power and that we believe is valid (that is, every one that credibly fulfils the second instrumental variables assumption). However, the instruments for a given political committee tend to be somewhat collinear, and this collinerity makes it difficult to interpret individual coefficients from the first stage equations. Our current set of first stage equations is maximally parsimonious, for the sake of our readers.

Consider the top panel of Table 1, which shows how a state's representatives on federal appropriations committees generate increase spending at research-type institutions. Every additional representative on the House appropriations committee raises research-type education expenditure by \$597 per person in the cohort, and every additional senator on the Senate appropriations committee raises research-type expenditure by \$419 per person in the cohort. (All dollar amounts are in 2004 dollars.) The F-statistic is 10.32 for the joint statistical significance of these two variables, which are the excluded instruments for spending on research-type education. That is, we have strong instruments.

It is worth noting that the partisan political variables, state effects, cohort effects, and regional time trends also explain considerable variation in research-type spending (compare the F-statistic to the overall R-squared statistic). We will not dwell on such variables which we treat merely as controls, but they are not unimportant.

The top panel of Table 2 shows how a state's representatives on federal appropriations committees generate increased numbers of research-type degrees. Every additional representative on the House appropriations committee raises the number of research degree holders by 0.485 per 10,000 people in the labor force. (Note that a state's labor force includes numerous cohorts, so this is not the same as 'per person in the cohort'. We normalize that the size of the labor force rather than the size of the cohort, because we ultimately want to see how investment in the cohort's education contributes to economic growth of the state, and a cohort can be larger or smaller relative to the state's labor force. However, the average ratio of labor force size to cohort size is 30, so the effect could be translated as 14.6 per 10,000 in the cohort or 0.146 percent of the cohort) Additional members on the Senate appropriations committee do not, however, have a statistically significant effect on the number of research degree holders. This suggests that some senators have delivered research grants to their states that have no, in fact, boosted research degree recipiency. As we noted earlier, there is room for spillage between an exogenous increase in educational spending and education attainment. People need not take up educational opportunities, perhaps especially of a high brow type.

The lower panels of Tables 1 and 2 show the results of similar exercises for lower levels of education. For instance, in the second panel of Table 1, we see that when a state education chairman has a four-year college in his area, spending at four-year colleges increases significantly. For every 1,000 four-year students enrolled his area, spending on four-year colleges rises by \$134 per person in the cohort and the number of baccalaureate degree holders rises by 0.79 per 10,000 in the labor force (about 0.24 percent of the cohort). Two-college spending and lower postsecondary attainment are influenced by similar variables but also appear to be boosted by the presence of manufacturing industries in the state education chairman's area. Perhaps local business leaders clamor for workers with vocational qualifications.

Our instrumental variables for four-year and two-year type education are generally quite strong, but they are consistently stronger at explaining spending (F-statistics of about 10) than they are at explaining educational degrees

(F-statistics of 5 and 8). In other words, as we expected, exogenous factors that boost investments in education do not always translate into additional educational attainment.

The point estimates in the bottom panel of Table 1 hint at the notion that a more progressive state supreme court raises expenditure on public elementary and secondary education, but the estimates are statistically insignificant. As discussed earlier, there are numerous reasons why this relationship is weak, including judges' poor understanding of school finance and progressive judges' emphasis on redistributing spending, as opposed to raising spending. We do not estimate first stage equations for the number of people with elementary and secondary educational attainment because virtually everyone in the U.S. has such qualifications. In any case, there is no reason to expect that additional spending on elementary and secondary schools would play out mainly in the form of higher attainment in grades kindergarten through twelve. Improvements in such schools might play out mainly in higher propensities to enroll in postsecondary education.

In all of the first stage equations shown, we relate political committee variables to spending and educational attainment that occurs in the state, regardless of where the state's students end up. It is worth investigating, however, whether a politically-motivated, exogenous boost in a state's educational investments raise educational attainment among a state's *residents*. In other words, once we allow for migration, do exogenous increases in various types of education spending raise a state's stock of human capital? We can answer this question by estimating versions of the first-stage equations like those shown in Table 2, except that we give a state credit for only those people who reside in it as adults. It "loses credit" for people whom it educates but who then emigrate. The results, some of which we show in Appendix Table 1, reveal that factors that produce exogenous increases in research-type spending have no effect on a state's number of residents with research-type degrees. Additional members on the House and Senate appropriations committees have no statistically significant effect on residents' tendency to hold research degrees. Since we know that additional members on the House appropriations committee boosted research degree recipiency among people born in the state, the results on residents suggest that people with research degrees are highly mobile and do not "stick" to the state in which they are educated. However, factors that produce exogenous increases in four-year and two-year college spending do have a statistically significant effect on a state's number of residents with baccalaureate degrees and lower postsecondary attainment. For instance, for every 1,000 four-year students enrolled the education committee chairman's area, the number of residents who are baccalaureate degree holders rises by 0.63 per 10,000 in the labor force. Comparing this effect to the one for the people a state educates (0.79 per 10,000), it appears that many baccalaureate degree holders stick in the state where they are educated. (Note, however, that the multicollinearity among the characteristics of a chairman's area should make us way of interpreting these two coefficients without simultaneously interpreting the related coefficients, some which suggest less "stickiness").

In summary, the first stage estimates suggest that political committee membership does generate significant variation in states' investment in education. However, exogenous increases in education spending do not always translate into degree attainment, and some of the additional educational attainment leaks out of the state through migration. People with research-type degrees are particularly prone to migrate.

7.2 Education investments measured by spending, economic growth associated with the state where it occurs

Table 3 shows our test of the model with all of its channels allowed to operate. Education investments are measured by spending, and we associate economic growth with the state where it occurs so that the effects of migration are felt. We show the coefficients and their robust standard errors at the top of the table, but it is easier to focus on the calculations that we base on the coefficients: the estimated effects for a typical far-from-the-frontier state (proximity of 0.25) and an at-the-frontier-state (proximity of 1.00).[22] We will focus on our preferred estimates, which are shown in the right-hand column. For these estimates, we instrument for distance to the frontier using patents as well as for the education variables. Note, however, that the estimates tend not to be terribly sensitive to our instrumenting for distance to the frontier.

Examining the right-hand column of Table 3, we see that a thousand dollars per person in additional spending on research-type education raises a state's annual per-employee growth rate by 0.269 percentage points if the state is at the frontier. It raises a state's per-employee growth rate by only 0.093 percentage points if the state is far from the frontier. (The average annual per-employee growth rate is 0.43 percentage points, but they vary widely: the standard deviation is 1.20 percentage points. Keep in mind that the growth rates are based on real dollars and are per employee.)

Moreover, a thousand dollars per person in additional spending on four-year type education raises an at-the-frontier state's per-employee growth rate by 0.057 percentage points, while the same spending *reduces* a far-from-the-frontier state's per-employee growth rate by 0.198 percentage points. Keep in mind that these effects are measured relative to what is typical for the state, cohort, and region. Thus, we do not mean that the average dollar of spending on four-year college education reduces growth for far-from-the-frontier states. Rather, we mean that marginal, exogenous boosts to spending on four-year college education reduce growth, presumably because they prevent a state from making other investments, including investments in lower brow human capital.

A thousand dollars per person in additional spending on two-year type education reduces an at-the-frontier state's per-employee growth rate by 0.055

[22] Robust standard errors must be used because the cohorts' educational experiences overlap, generating substantial serial correlation in the education investments experienced by adjacent cohorts.

percentage points, but the same spending raises a far-from-the-frontier state's per-employee growth rate by 0.474 percentage points. Since our instruments for spending on elementary and secondary education work poorly, we should give very little weight to the estimated coefficients. However, if we interpret them (just as an illustration), we see that a thousand dollars in additional spending on elementary and secondary education reduces growth in an at-the-frontier-state by 0.206 percentage points and has no statistically significant effect on growth for far-from-frontier states.

On the whole, these results support the model and suggest that close-to-frontier states derive much greater growth from investments in high brow education than far-from-frontier states do. The reverse also holds. Investment in low-brow education generate growth in far-from-frontier states but not in states at the frontier. It is worth noting that the results suggest where split between high brow and low brow education occurs in the U.S. Four-year college and research-type education are high brow–they are more growth-enhancing in states closer to the frontier–while two-year college type education is low brow.

Finally, as a specification check, the bottom of Table 3 shows that we obtain similar results if we do not use data on every cohort, but instead use cohorts spaced in order to minimize the overlap in their postsecondary experiences. We space cohorts every five years, namely the birth cohorts of 1947, 1952, 1957, 1962, 1967, and 1972. The similarity in the results between the top and bottom of Table 3 suggests that our results do not change dramatically when we reduce serial correlation in educational investments by using spaced cohorts.[23]

7.3 Education investments measured by spending, economic growth apportioned to states based on where people were born

Table 4 shows our test of the model when we shut down the migration channel by apportioning economic growth to states based on where people were born. To create an extreme example for illustration, suppose that all of California's residents with a research-type education were born (and, we surmise, usually educated) in Connecticut. Then the economic growth rate associated with each of these California residents' cohort would be apportioned back to Connecticut. Connecticut thus gets "growth credit" from California, according to its impact on California's labor force. Other than our un-doing migration, the Table 4 is constructed exactly like Table 3.

Examining the right-hand column of Table 4, we see that a thousand dollars per person in additional spending on research-type education raises a state's annual per-employee growth rate by 0.157 percentage points if the state is at the frontier. It raises a state's per-employee growth rate by only 0.041 percentage points if the state is far from the frontier. For comparison, these same two

[23] In fact, we can go further and space cohorts at eight year intervals. The results retain the same broad character but, unsurprisingly, they vary somewhat depending on exactly which four cohorts we choose.

calculations were 0.269 percentage points and 0.093 percentage points in Table 3, where we had not shut down migration. Consider the overall difference between the growth effects of research-type spending in at-the-frontier and far-from-the-frontier states. It is 0.178 percentage points with migration, and it is 0.116 percentage points with migration un-done. These numbers suggest that migration of research-type investment accounts for about one-third of the total difference in growth effects between at-the-frontier states and far-from-frontier states. The remaining two-thirds of the difference is associated with the reallocation (Rybzcynski) effect and indirect effects.

The right-hand column of Table 4 also shows that a thousand dollars per person in additional spending on four-year type education raises an at-the-frontier state's per-employee growth rate by 0.051 percentage points, while the same spending *reduces* a far-from-the-frontier state's per-employee growth rate by 0.038 percentage points. If we compare these numbers with their counterparts in Table 3, we will see that migration of four-year type education investments accounts for about 60 percent of the total difference in growth effects between at-the-frontier states and far-from-frontier states.

A thousand dollars per person in additional spending on two-year type education reduces an at-the-frontier state's per-employee growth rate by 0.024 percentage points, but the same spending raises a far-from-the-frontier state's per-employee growth rate by 0.236 percentage points. Another comparison with the parallel results in Table 3 suggests that migration of two-year type education investments account for a little less than half of the total difference in growth effects between at-the-frontier and far-from-frontier states.

We do not want to make too much of migration accounting that depends on individual point estimates because point estimates have standard errors and rely differently on our instrumental variables. Thus, we take an overall impression, which is that migration appears to account for about half of the difference in growth effects between far-from-the-frontier and at-the-frontier states.

Note that Table 4 reaffirms our conclusion that the division between high brow and low brow education occurs in the U.S. somewhere between baccalaureate degrees and lower postsecondary degrees. Also, our specification check (at the bottom of Table 4) suggests that our results do not change dramatically when we reduce serial correlation in educational investments by using spaced cohorts.

7.4 Education investments measured by attainment, economic growth associated with the state where it occurs

We will go more quickly through the results that based on measuring educational investments with attainment. The main reason we show these results is that we shut down some of the indirect channels in the model by looking at attainment. In particular, if a dollar of research-type spending generates a greater number of skilled workers in a close-to-the-frontier state, we have shut down that indirect channel for differences in growth effects. Also, we are interested in whether attainment-based results broadly confirm the results based on education spending. There are a number of differences between the spending data (which is contemporaneous administrative data) and the attainment data (which is retrospective survey data). For one thing, spending is in units (real dollars) that are quite consistent over time, but there is no guarantee that attainment is in similarly consistent units. The content of research, baccalaureate, and lower postsecondary degrees changes over a span of 25 years. In short, we are looking for broadly similar patterns; it would be naive to expect an exact correspondence between the spending-based results and the attainment-based results.

Table 5 shows our attainment-based results in which we allow the migration channel to operate (we associate economic growth with the state in which it occurs). The estimates in the right-hand column indicate that an additional research degree holder per 10,000 people in the labor force raises the annual per-employee real economic growth rate by 0.425 percentage points for a state at the frontier. The same additional research degree holder lowers the per-employee growth rate 0.731 percentage points for a state far from the frontier. For reference, remember that having a member on the House appropriations committee raises a state's number of research degree recipients by 0.485 per 10,000 people in the labor force. Thus, a realistic shock to a state's production of research-type degrees might raise its growth rate by 0.21 percentage points if the state is right at the technology frontier or lower its growth rate by 0.36 percentage points if the state is as far from the technology frontier as U.S. states tend to be.

The estimates in the right-hand column also show that an additional baccalaureate degree holder has little effect on growth either in at-the-frontier or far-from-the-frontier states. The computations are not statistically significantly different from zero and are sensitive to whether we instrument for proximity to the frontier. A comparison between this result and the results for spending on four-year type education may indicate that the indirect effects of spending on four-year colleges are important, so that shutting them down attenuates much of the effect. However, this is only one way to reconcile the spending and attainment results. It may be that the division between high brow and low brow education actually falls somewhere *within* the holders of baccalaureate degrees, with more expensive four-year education tending to be high brow and less expensive four-year education tending to be low brow. Alternatively, changes over time in the content of baccalaureate degrees or changes in the distribution of four-year college spending may reconcile the results.

The results in Table 5 indicate that additional lower postsecondary degree attainment has no statistically significant effect on growth either in at-the-frontier or far-from-the-frontier states. However, the point estimates go in the same direction as those based on spending: two-year college type education is more conducive to growth in far-from-frontier states than in close-to-frontier states.

In summary, the attainment-based results broadly confirm the results based on spending, especially for research-type education which is most obviously crucial to technological innovation. While the results are consistent with the idea that education investments have important indirect effects (that are lost when we focus only on attainment), we are wary of forcing this interpretation on the data because the results are also consistent with a number of other, more mundane interpretations. The specification check shown at the bottom of Table 5 shows that our results display the same broad patterns when spaced cohorts are used, rather than all available cohorts.

7.5 Education investments measured by attainment, economic growth apportioned to states based on where people were born

Finally, in Table 6, we show results when we un-do migration and eliminate certain indirect effects of educational spending. In other words, Table 6 is the same as Table 5 except that we shut down migration by apportioning economic growth to states based on where people were born (and, we presume, usually educated). We will focus on the results for research-type degrees because the estimates for lower degrees are modest or statistically insignificant, making it difficult to conduct comparisons with (similarly) modest or statistically insignificant estimates from Table 5.

The estimates in the right-hand column of Table indicate that an additional research degree holder per 10,000 people in the labor force raises the annual per-employee real economic growth rate by 0.276 percentage points for a state at the frontier. The same additional research degree holder lowers the per-employee growth rate 0.429 percentage points for a state far from the frontier. For comparison, these same two estimates were an increase of 0.425 percentage points and a reduction of 0.731 percentage points in Table 5. The comparison suggests that migration accounts for about 40 percent of the difference in growth effects between at-the-frontier and far-from-the-frontier states. This calculation of migration's role broadly accords with the accounting we obtained from the spending-based results.

The specification check shown at the bottom of Table 6 shows that our results display the same broad patterns when spaced cohorts are used, rather than all available cohorts.

8 Discussion

Empirically, we find strong support for the hypothesis that investments in high brow education are substantially more growth enhancing for states that are close to the technological frontier. We also find support for the converse: investments in low brow education are substantially more growth enhancing for states that are far from the technological frontier. For the U.S., the data suggest that the division between high brow and low brow education falls such that research type education and four-year college education (possibly only more expensive four-year college education) are high brow and lower postsecondary education is low brow. In the context of our model, research type and baccalaureate education are useful for innovating; lower postsecondary education is useful for imitating.

When we allow all of the channels in the model to operate, we obtain results as follows. A thousand dollars per person in additional spending on research-type education raises an at-the-frontier state's annual per-employee growth rate by 0.269 percentage points but raises a far-from-the-frontier states' per-employee growth rate by only 0.093 percentage points. A thousand dollars per person in additional spending on four-year college type education raises an at-the-frontier state's per-employee growth rate by 0.057 percentage points, while the same spending reduces a far-from-the-frontier state's per-employee growth rate by 0.198 percentage points. A thousand dollars per person in additional spending on two-year college type education reduces an at-the-frontier state's per-employee growth rate by 0.055 percentage points, but the same spending raises a far-from-the-frontier state's per-employee growth rate by 0.474 percentage points.

Using calculations that un-do migration, we can shut down the channel by which migration exacerates differences in growth effects between at-the-frontier and far-from-the-frontier states. When we do this, we find that the migration channel accounts for about half of the total difference between at-the-frontier and far-from-the-frontier states. Our most reliable estimates, which are based on research type education, assign migration slightly smaller role of 33 to 40 percent. In short, the reallocation (Rybzcynski) effect, by which highly educated labor causes capital to be reallocated to innovative technologies, accounts for at least half of the total differences in growth effects between at-the-frontier and far-from-the-frontier states. We present evidence consistent with the hypothesis that investments in education have important indirect effects. However, this evidence is also consistent with more mundane explanations related to measurement issues.

We are particularly confident about our results for research-type education. They are very consistent across specifications and a variety of data. Also, our instrumental variables for spending on research-type education are highly credible and work well. The paper also contains a number of other empirical contributions: instruments, measures of proximity to the frontier, methods for estimating migration of educated workers, and so on.

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9 Appendix 1: Proofs of Lemmas 1,2, and 4

9.1 Proof of Lemma 1

When both imitation and innovation are performed in equilibrium, the intermediate good producer's maximization program leads to the first order conditions (7) and (6). Taking the ratio of (7) over (6), one gets

$$\frac{u_m}{s_m} = \psi \frac{u_n}{s_n} \tag{15}$$

which implies (8) and (9) after substituting (15) back into (7) and (6).

9.2 Proof of Lemma 2

The equilibrium rate of productivity growth is given by

$$g_{A,t+1} = \frac{A_{t+1} - A_t}{A_t}$$

Substituting for u_m, u_n, s_m and s_n using Lemma 1, we immediately get

$$g_A/\lambda = s_m(\frac{\Psi}{h(a)})^\sigma + \gamma(\hat{S} - s_m)(\frac{1}{h(a)})^\phi$$

Lemma 1 also implies that

$$s_m = \frac{h(a)\hat{U} - \hat{S}}{\Psi - 1}$$

which can be substituted in the preceding equation to yield Lemma 2.

9.3 Proof of Lemma 4

Part (a) Taking the first-order conditions (7) and (6) then substituting for the skilled and unskilled wages (1) and (2) ,

we obtain:

$$w_{s,t+1} = \zeta(1-\beta)A_{t+1}U^{\beta}_{f,t+1}S^{-\beta}_{f,t+1} = \delta(U^{\beta}_{f,t+1}S^{1-\beta}_{f,t+1})\lambda(1-\sigma)u^{\sigma}_{m,t+1}s^{-\sigma}_{m,t+1}(\bar{A}_t - A_t) \tag{16}$$

and

$$w_{u,t+1} = \zeta\beta A_{t+1}U^{\beta-1}_{f,t+1}S^{1-\beta}_{f,t+1} = \delta(U^{\beta}_{f,t+1}S^{1-\beta}_{f,t+1})\lambda u^{\sigma-1}_{m,t+1}s^{1-\sigma}_{m,t+1}(\bar{A}_t - A_t) \tag{17}$$

which imply

$$\zeta(1-\beta)A_{t+1} = \delta S_{f,t+1}\lambda(1-\sigma)u^{\sigma}_{m,t+1}s^{-\sigma}_{m,t+1}(\bar{A}_t - A_t) \tag{18}$$

and

$$\zeta\beta A_{t+1} = \delta U_{f,t+1}\lambda\sigma u^{\sigma-1}_{m,t+1}s^{1-\sigma}_{m,t+1}(\bar{A}_t - A_t) \tag{19}$$

The equilibrium conditions (18) and (19) constitute a system of two linear equations in two unknowns, $\hat{U}$ and $\hat{S}$. After some algebra, this system can be rewritten:

$$\begin{pmatrix} 1+\frac{\delta}{\beta\zeta} & \frac{1-\phi}{\phi}\frac{1}{h(a)} \\ \frac{\phi}{1-\phi}h(a) & 1+\frac{\delta}{(1-\beta)\zeta} \end{pmatrix} \begin{pmatrix} \hat{U} \\ \hat{S} \end{pmatrix} = \begin{pmatrix} \frac{\delta}{\beta\zeta}U - \frac{h(a)^{(\phi-1)}}{\phi\lambda\gamma} \\ \frac{\delta}{(1-\beta)\zeta}S - \frac{h(a)^{\phi}}{(1-\phi)\lambda\gamma} \end{pmatrix},$$

the solution of which is

$$\begin{pmatrix} \hat{U} \\ \hat{S} \end{pmatrix} = \frac{1}{1+\frac{\delta}{\zeta}} \begin{pmatrix} [(1-\beta)+\frac{\delta}{\zeta}]U - \frac{1-\phi}{\phi}\frac{1}{h(a)}\beta S - \beta\frac{h(a)^{\phi-1}}{\phi\lambda\gamma} \\ -\frac{\phi}{1-\phi}h(a)(1-\beta)U + (\beta+\frac{\delta}{\zeta})S - (1-\beta)\frac{h(a)^{\phi}}{(1-\phi)\lambda\gamma} \end{pmatrix}$$

which, given that $\delta/\zeta = \alpha^{-3}$, can be rewritten as in Lemma 2.

Part (b): Conditions for interior solution

An interior solution obtains if and only if both s_m and s_n are strictly positive. Given Lemma 1, these two conditions are equivalent to:

$$\begin{aligned} h(a)\hat{U} - \hat{S} &> 0 \\ \Psi\hat{S} - h(a)\hat{U} &> 0 \end{aligned}$$

which together yield part (b), once $\hat{U}$ and $\hat{S}$ have been replaced by the expressions given in part (a).

Part (c):

Condition for solution with innovation but without imitation

An equilibrium with innovation but without imitation must be such that the marginal product of both types of labor is equalized across innovation and final good production. This yields:

$$1+\lambda\gamma\hat{U}^{\phi}\hat{S}^{1-\phi} = \frac{\delta}{\zeta\beta}(U-\hat{U})\lambda\gamma\phi\hat{U}^{\phi-1}\hat{S}^{1-\phi} \tag{20}$$

and

$$1+\lambda\gamma\hat{U}^{\phi}\hat{S}^{1-\phi} = \frac{\delta}{\zeta(1-\beta)}(S-\hat{S})\lambda\gamma(1-\phi)\hat{U}^{\phi}\hat{S}^{-\phi}$$

Taking the ratio of these two expressions, one obtains:

$$\frac{U_f}{S_f} = \Gamma\frac{\hat{U}}{\hat{S}}$$

which can be transformed in

$$\hat{U} = \frac{U\hat{S}}{\hat{S}+\Gamma(S-\hat{S})}$$

Substituting this expression into (20), one obtains the following equation in $\hat{S}$:

$$\frac{1}{\lambda\gamma}[\frac{\Gamma S+(1-\Gamma)\hat{S}}{U}]^{\phi} = \frac{\delta\phi}{\zeta\beta}\Gamma S - \hat{S}(1+\frac{\delta\phi}{\zeta\beta}\Gamma)$$

After plotting the LHS and the RHS, it is straightforward to see that innovation takes place in equilibrium only if

$$S > \frac{1}{\Gamma}(\frac{\zeta\beta}{\delta\phi\lambda\gamma})^{\frac{1}{1-\phi}} U^{-\frac{\phi}{1-\phi}} \tag{21}$$

Condition for solution with imitation but without innovation

In this case, the equilibrium is characterized by

$$\frac{a}{1-a} + \lambda\hat{U}^{\sigma}\hat{S}^{1-\sigma} = \frac{\delta}{\zeta\beta}(U - \hat{U})\lambda\sigma\hat{U}^{\sigma-1}\hat{S}^{1-\sigma} \tag{22}$$

and

$$\frac{a}{1-a} + \lambda\hat{U}^{\sigma}\hat{S}^{1-\sigma} = \frac{\delta}{\zeta(1-\beta)}(S - \hat{S})\lambda(1-\sigma)\hat{U}^{\sigma}\hat{S}^{-\sigma}$$

Taking the ratio of these two equalities yields

$$\frac{U_f}{S_f} = \Delta\frac{\hat{U}}{\hat{S}}$$

then

$$\hat{U} = \frac{U\hat{S}}{\hat{S} + \Delta(S - \hat{S})}$$

and then

$$\frac{1}{\lambda}(\frac{a}{1-a})[\frac{\Delta S + (1-\Delta)\hat{S}}{U}]^{\sigma} = \frac{\delta\sigma}{\zeta\beta}\Delta S - \hat{S}(1 + \frac{\delta\sigma}{\zeta\beta}\Delta)$$

After plotting the LHS and the RHS, it is straightforward to see that imitation takes place in equilibrium only if

$$S > \frac{1}{\Delta}(\frac{\zeta\beta}{\delta\sigma\lambda}\frac{a}{1-a})^{\frac{1}{1-\sigma}} U^{-\frac{\sigma}{1-\sigma}} \tag{23}$$

Condition for solution with neither imitation nor innovation

The hyperbolic curve delimiting the area with innovation without imitation (defined by condition (21)) and that delimiting the area with imitation without innovation (defined by condition (23)) intersect only once at (U^*, S^*). Because $\sigma > \phi$ by Assumption 1, the area without any technological progress is then defined by

$$S < \min(\frac{1}{\Gamma}(\frac{\zeta\beta}{\delta\phi\lambda\gamma})^{\frac{1}{1-\phi}} U^{-\frac{\phi}{1-\phi}}, \frac{1}{\Delta}(\frac{\zeta\beta}{\delta\sigma\lambda}\frac{a}{1-a})^{\frac{1}{1-\sigma}} U^{-\frac{\sigma}{1-\sigma}})$$

This establishes Lemma 4.

10 Appendix 2: Proof of Proposition 3

Using (11) to replace S_f in equation (13), one gets:

$$M\mu^* = \frac{\overline{w}_{t+1}}{\bar{A}_t} - \frac{\delta\lambda\gamma(1-\phi)}{1+\frac{\delta}{\zeta}} h(a)^{-\phi} a[\frac{\phi}{1-\phi} h(a)]^{1-\beta}[U + \frac{1-\phi}{\phi}\frac{1}{h(a)} S(1-\mu^*) + \frac{h(a)^{\phi-1}}{\phi\lambda\gamma}] \tag{24}$$

The RHS is linear in U and S and therefore from there it is straightforward to obtain parts (i) and (ii) of the Proposition. Part (iii) follows directly from (13) and the fact that, from (10) and (16),

$$w_{t+1} \sim A_{t+1} h(a)^{-\beta}$$

where

$$A_{t+1} = (1+g_A)\bar{A}_t a.$$

Finally, differentiating equation (24) with respect to S, one gets:

$$\frac{\partial \mu^*}{\partial S} = \frac{-(1-\mu^*)}{M h(a)^{1+\phi} a^{-1} [\frac{\phi}{1-\phi} h(a)]^{\beta-1} \frac{\phi}{1-\phi} \frac{1+\frac{\delta}{\zeta}}{\delta\lambda\gamma(1-\phi)} - S}$$

which is a decreasing function of a which proves part (iv) of the Proposition.

11 Data Appendix

This appendix records additional detail on sources of information and methods that we used to construct variables in our panel data set.

11.1 Instrumental Variables Based on Political Committees

11.1.1 I. Federal Appropriations Committees

Membership on the federal (U.S. House and Senate) appropriations committees is recorded in the Congressional Staff Directories. We collected committee rosters from 1950 to 2002. We then matched each representative or senator to his biographical information, also in the Congressional Staff Directories. In particular, we recorded each member's state, political party, subcommittee assignments, position as a subcommittee chairperson or ranking member, and tenure in the House or Senate.

Savage (1999) reports that 50 percent of earmarks for academic research are authorized by just two subcommittees: Defense and Agriculture. Energy is the next largest grantor. We defined an indicator for membership on one of these three "key" committees. Payne (2001) notes that junior senators are more effective at bringing federal research dollars to their state. Following her classification, we created three tenure categories in the House (Senate): 0-6 years (0-8); 7-11 years (9-13) and 11+ years (14+). We also grouped representatives and senators according to whether they belong to the majority or minority party in a given year.

In an effort to be parsimonious enough to show interpretable first-stage coefficients, we use as instrumental variables just a state's number of members on the House and Senate appropriations committees. These variables are summed for the years a cohort would logically be in graduate education (ages 22 to 25). If parsimony is less important (that is, if we do not mind a first-stage equation with multicollinearity among the instruments), we can use a greater array of the measures we constructed based on the federal appropriations committees. However, we get much of the available explanatory power from the two measures we show.

11.1.2 II. Chairmen of State Education Committees

Starting in 1975, the Council of State Governments began publishing a series of national directories to state legislatures. From the volumes entitled *State Legislative Leadership, Committees and Staff*, we collected the name of the chairperson of committees involved in education policy. Using the companion volumes entitled *Selected State Officials and the Legislatures*, we matched these legislators to their street addresses and district numbers.

Before 1975, state legislative information is only available in state's own political directories or state's senate journals. These vary widely in their organization and detail. All states with political directories that were archived in the

Harvard library system were used at Harvard. Legislative information for other states, whose directories were not archived at Harvard or whose directories did not include standing committee assignments, was gathered with the assistance of librarians in state law libraries. A complete list of state-specific sources is available from the authors upon request.

Ideally, we would link state education committee chairmen to the demographic and socio-economic characteristics of exact geographic area that defines their constituency. However, before 1990, Census data was not matched to state senatorial districts. Furthermore, because the boundaries and numbering of districts change over time, if we "retroject" the 1990 boundaries back in time using digital mapping tools, we will get incorrect demographic and socio-economic characteristics. Instead, we match state legislators to the characteristics of their locality using 3-digit zip codes. We chose 3-digit, rather than 5-digit, zip codes because they are roughly the same size as state senatorial districts and are less prone than their smaller counterparts to change over time. Zip codes were developed by the US Postal Service in 1963. For legislators in office before 1963, we match their street addresses to contemporary zip code using the Postal Service website (www.usps.com); if we only know the town of residence, we find the contemporary zip code(s) for that town using www.city-data.com.

Using the U.S. Census Summary Tape Files, we link a senator to the following characteristics of his 3-digit zip code area in 1970: share black, share Latino, mean family income, share of families earning $15,000 or more ($, 1970), share of individuals with various levels of completed education, and share employed in various industries. We also use the Integrated Postsecondary Education Data System (IPEDS) to count by 3-digit zip code area the number of institutions of higher education by highest degree granted and the number of students enrolled in each type of institution per capita. We expect that senators who represent a highly educated population, and/or who have colleges and universities in their district, will be more likely to support the state's four-year college system. Similarly, senators who represent constituents with a high school education, or some college, and/or who have community colleges in their district, will support two-year colleges, and so on.

11.1.3 III. State Supreme Court

Our method for inferring the political affiliation of a state supreme court justice depends on the state's process of judicial selection. For states that rely on gubernatorial or legislative appointment, we assume that judges appointed by a Democratic governor or legislature will have a Democratic judicial philosophy (and, likewise for Republicans). 10 non-southern states appointed judges at the beginning of our data collection period in 1951, while 22 used this system by 1991. At the beginning of the period, the remaining 25 non-southern states elected their judges, either in partisan (10) or non-partisan (15) elections. We collected declared party affiliation for these judges when possible from judicial directories; this information is available for 78 percent of judges in partisan states and 62 percent of judges in non-partisan states. In the remaining cases, we use the political party of the governor voted into office in the most recent election.

To match judges with their appointing governor, we first inferred each judge's year of appointment to the bench by comparing the court's composition over time. Lists of sitting judges can be found from 1951 on in the *Book of the States, Supplement I*, subtitled variously *Elective Officers of the States* or State Elective Officials and the Legislatures. We looked up the years of first appointment for judges already on the bench in 1951 in state political directories. Information on the political party of sitting governors is available from a number of sources; we used Candidate and Constituency Statistics of Elections (ICPSR Study No. 7577). Finally, we collected the political affiliation of elected judges from short biographies published in the Directory of American Judges (Liebman, 1955) or The American Bench; Judges of the Nation (1977 on).

In southern states, declared political affiliation is not an informative signal of preferences for redistribution because of the monolithic control of the Democratic party. Instead, we use the above-mentioned judicial directories, along with Who's Who in the South and Southwest, to collect biographical information about each judge, including his/her county of birth, religion, law school alma mater and service on a law school faculty. Our goal is to discover patterns in these measures that map onto the political spectrum; for this, we use factor analysis.

In his seminal study, Southern Politics in State and Nation, Key (1949) identifies two major political blocs in the South: the populists, an alliance of small farmers and the urban working class, and conservative white planters. To determine the background of our judges, we match their counties of birth to a series of economic and agricultural characteristics, and to political variables from two key elections, those of 1928 and 1948, which divided the "solid" South. In particular, we measure the share of the electorate that voted Republican in 1928 – in protest of the Catholic Democratic candidate, Al Smith – and the share that voted for the State's Rights party in opposition to President Truman's support for Civil Rights.

The factor loadings closely correspond to Key's history of southern political factions. Growing up in a cotton county with a large share of tenant farmers and low diffusion of tractors is positively associated with what we call the "conservative" factor, as is being a Baptist and attending your state's flagship campus for law school (as opposed to being educated out of state). Being an Episcopalian or Presbyterian and growing up in an urban county are negatively associated with this factor. As we would expect, "conservative" judges hail from counties with a high concentration of State's Rights voters, who were also less likely to break their Democratic loyalties in the election of 1928.

11.2 Measures of Educational Investment Based on Spending

11.2.1 Elementary and Secondary Public School Spending

Data on spending in elementary and secondary public schools are taken from the *Digest of Education Statistics* (1971 to 2004) for the school years from 1966-67 to 2001-02. We record total expenditure. These data are at the level of the state and school year. For prior years, we rely on *Biennial Reports of the United States Office of Education* (1950 to 1968). These data are at the level of the state and cover the 1947-48 to 1965-66 school years. For the school years prior to 1963-64, we have data only on years that begin with an odd number. We use linear interpolation for the intervening years. Spending data are put into real dollars using the annual Consumer Price Index (CPI-U) for the United States. We divide spending in each school year by the total population aged five to seventeen at the time. See below for information on the population by age data.

11.2.2 Spending on Two-Year College Type Education

For spending on two-year college type education, we record the total expenditures of postsecondary institutions that have a Carnegie classification of "Two Year" or that have "Two Year" as their highest degree granted.

For the school years from 1966-67 to 1992-93, we use data from the financial files of CASPAR (National Science Foundation, 2005). Note that CASPAR is a longitudinal compilation of data taken from two data sources based on postsecondary institutions annual self-reports: the Higher Education General Information System and the Integrated Postsecondary Education Data System. When necessary, we use data from the two basic data sources to clarify unusual values and fill in missing observations in CASPAR. For the most recent school years, spending data are not yet available in the CASPAR data. Thus, for the school years from 1993-94 to 1997-98, we use data from the financial and institutional characteristics files of the Integrated Postsecondary Education Data System (United States Department of Education, 1994 to 1998). Because CASPAR contains a slightly limited subset of postsecondary institutions, we impose the CASPAR frame on the basic sources. This ensures that we do not create "seams" or other anomalies in the dataset when we clarify or amplify it using data from the basic sources.

Note that Carnegie classifcations are recorded in CASPAR as an institutional characteristic.

11.2.3 Spending on Research Type Education

For spending on research type education, we record the total expenditures of postsecondary institutions that are not two-year type institutions (see above) that fit into one of the following categories: institutions with a "Research 1" Carnegie classification; institutions with a "Research 2" Carnegie classification;

institutions that grant the doctoral degree and that have a "Medical" Carnegie classification; institutions that grant the doctoral degree and that have a "Engineering" Carnegie classification.

The data on spending on research type education are from the same sources as the data on spending on two-year type education.

11.2.4 Spending on Four-Year Type Education

For spending on four-year type education, we record the total expenditures of postsecondary institutions that are not two-year type or research type institutions (see above). In addition, to be of the four-year type, an institution must grant the baccalaureate degree or a higher degree (masters, professional, doctoral). Note that, by design, the two-year, research, and four-year types are mutually exclusive.

The data on spending on research type education are from the same sources as the data on spending on two-year type education.

11.3 Measures of Population by Age

Measures of population by single year of age are traditionally estimated using a combination of data from the decennial United States Censuses of Population, vital statistics data, immigration data, and state administrative data. The measures are known as intercensal estimates because, in the Census years, population data by single year of age are recorded. Intercensal estimates are currently prepared by the Population Division of the United States Bureau of the Census, and we use their estimates for 2000 to 2004 (United States Bureau of the Census, 2005). The Population Division's webpage (see references) contains details on the methodology they use for the estimation. For the years from 1969 to 1999, we use estimates prepared by the National Cancer Institute using a methodology very similar to that of the Population Division (National Cancer Institute, 2005). The National Cancer Institute's webpage (see references) contains details on their methodology.

For the years from 1950 to 1969, we use Census data and interpolate between the Censuses. The data are not drawn directly from a Census publication but are instead drawn from a variety of sources that, in turn, drew Census data. These are Haines (2004); Department of Labor and Workforce Development, State of Alaska (2000); Department of Business, Economic Development and Tourism, State of Hawaii (1997); Hobbs and Stoops (2002), and Schmitt (1977).

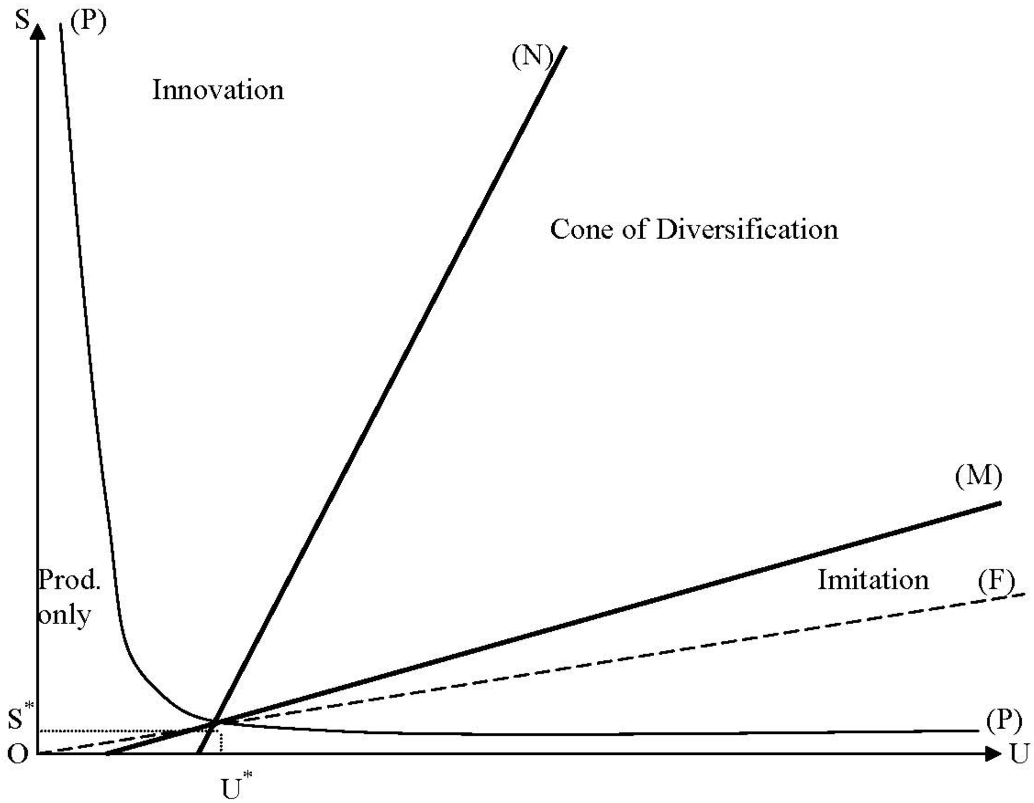

FIGURE 1 (case $\Delta>1$)

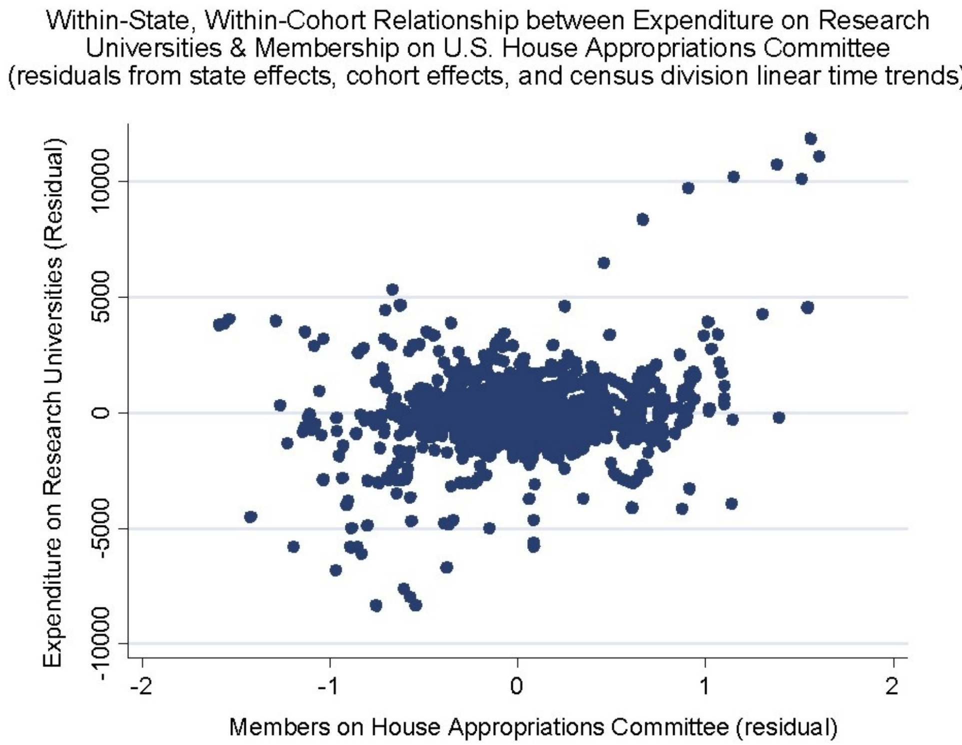
Within-State, Within-Cohort Relationship between Expenditure on Research
Universities & Membership on U.S. House Appropriations Committee
(residuals from state effects, cohort effects, and census division linear time trends)
Expenditure on Research Universities (Residual)
10000
5000
0
-5000
-10000
-2
-1
0
1
2
Members on House Appropriations Committee (residual)

Figure 2

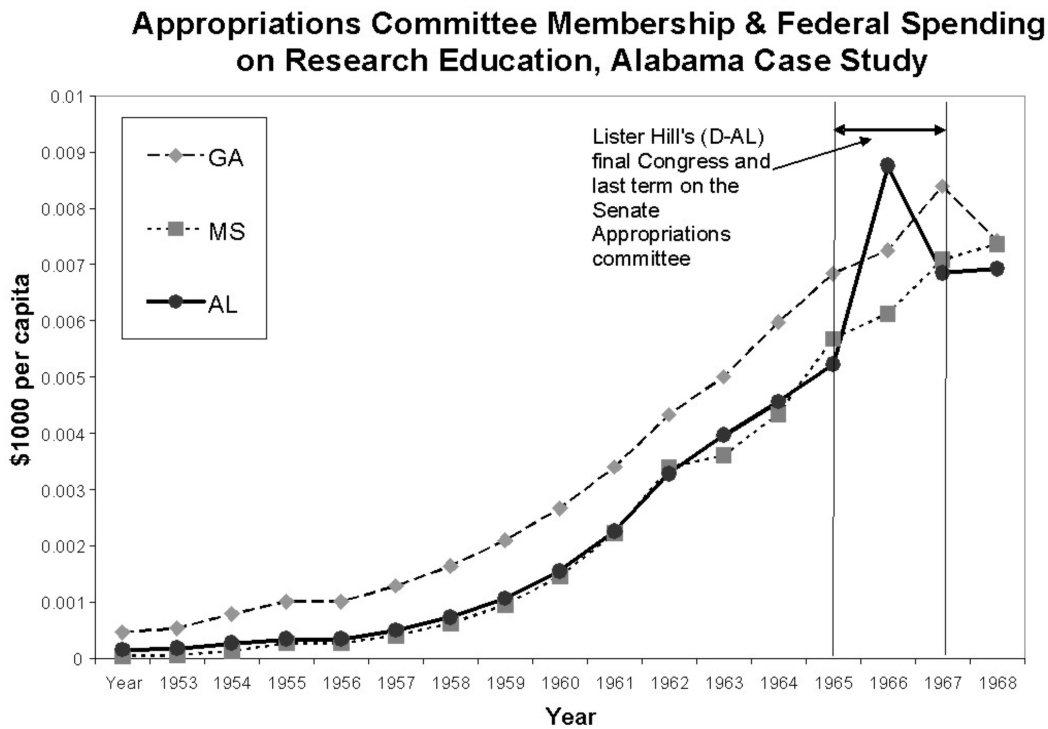

Figure 3

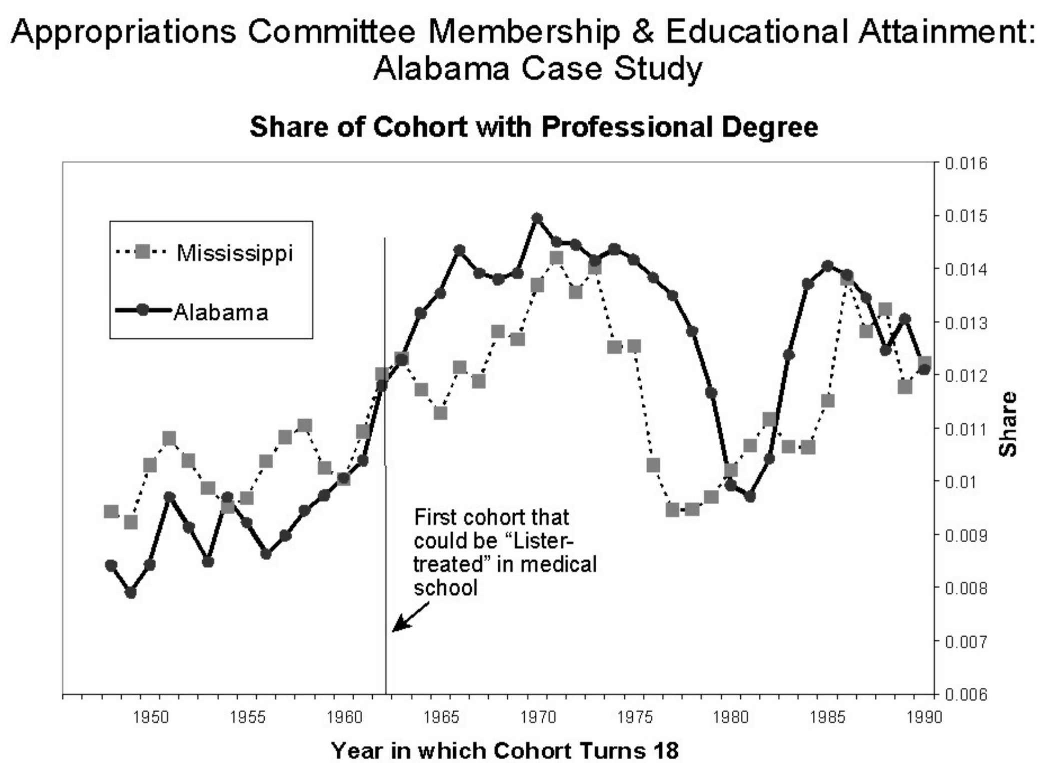

Figure 4

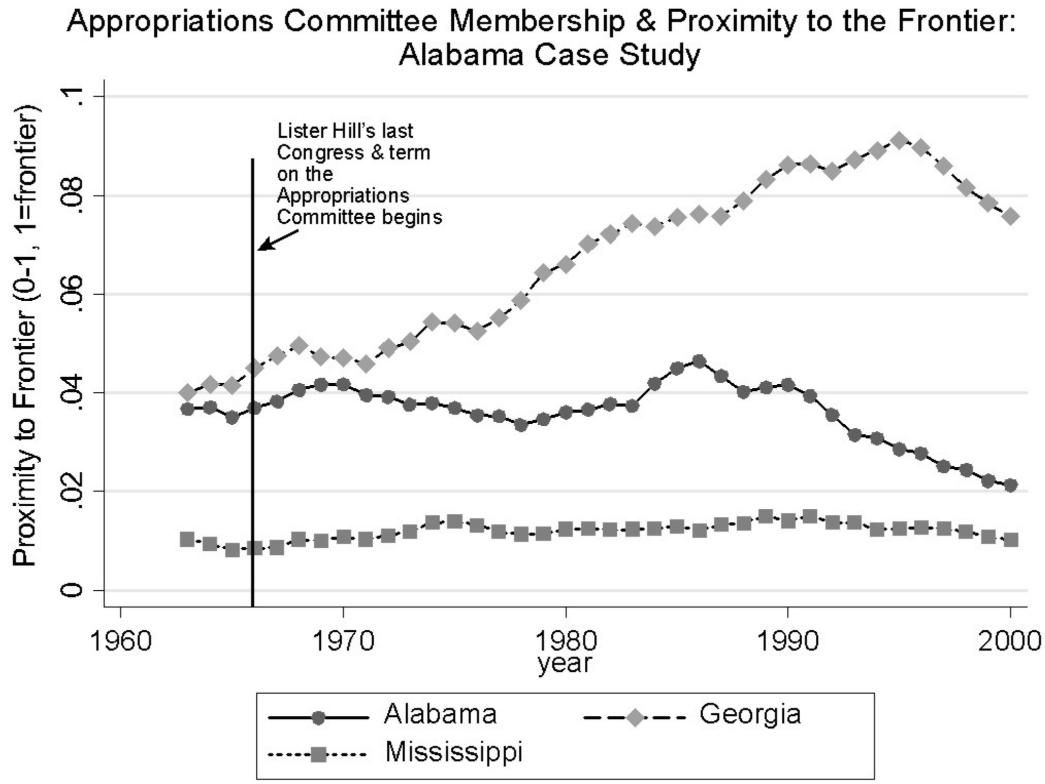

Figure 5

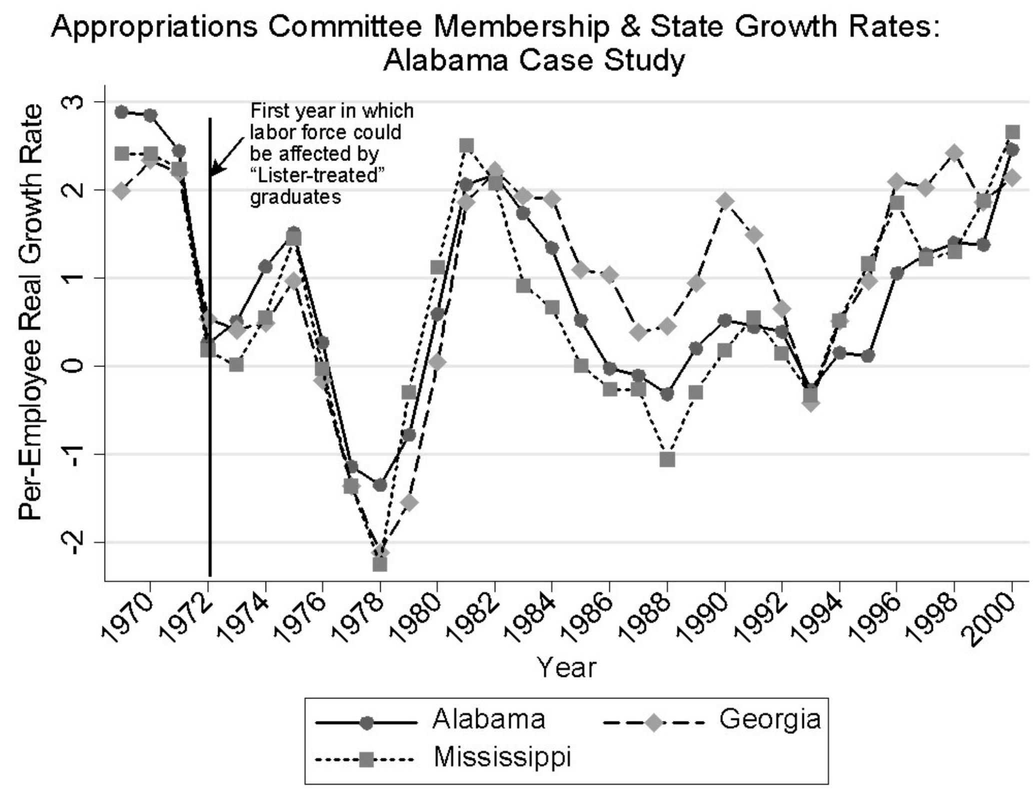

Figure 6

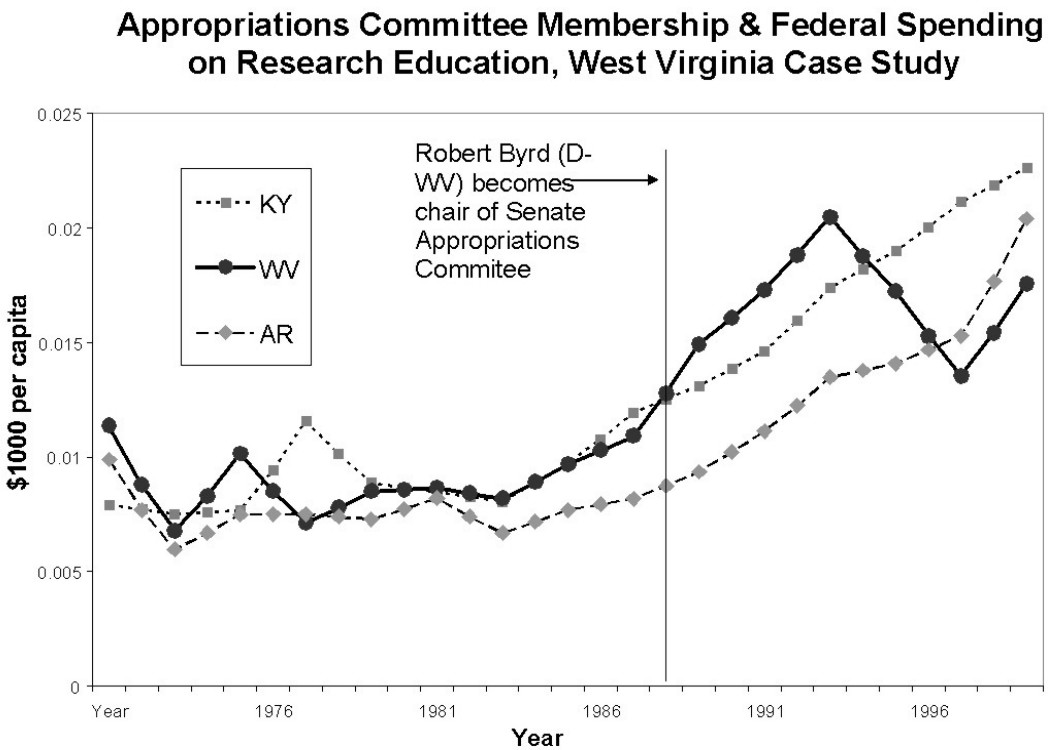

Figure 7

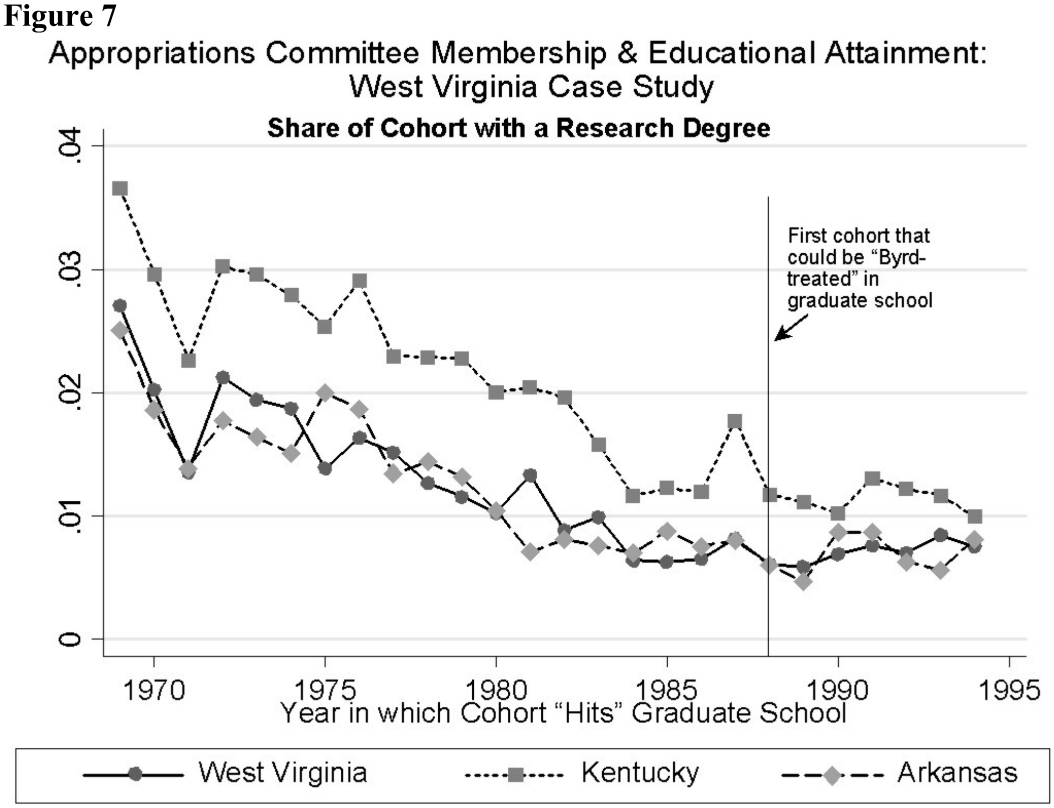

Figure 8

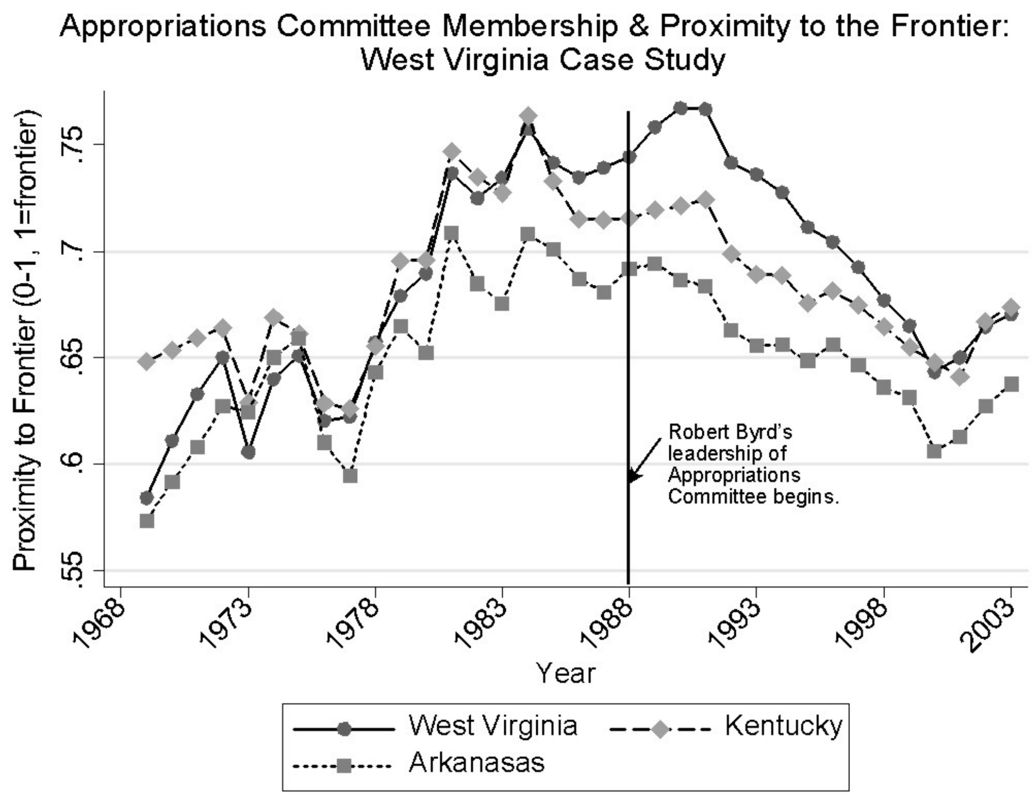

Figure 9

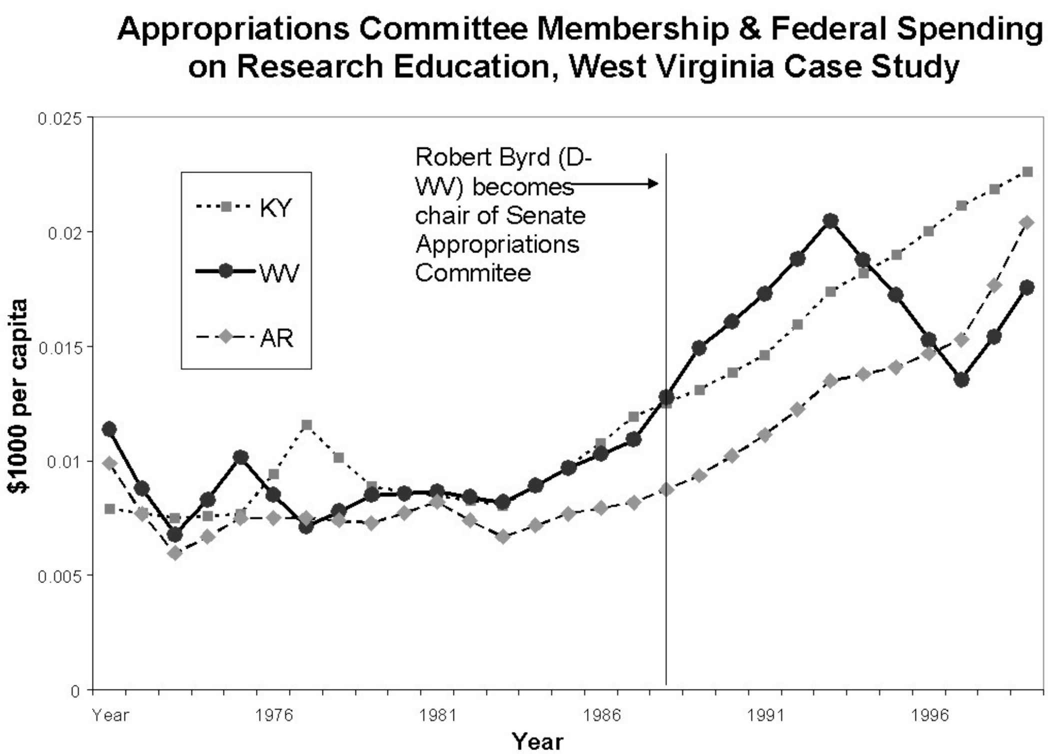

Figure 10

Appropriations Committee Membership & Federal Spending on Research Education, Massachusetts Case Study

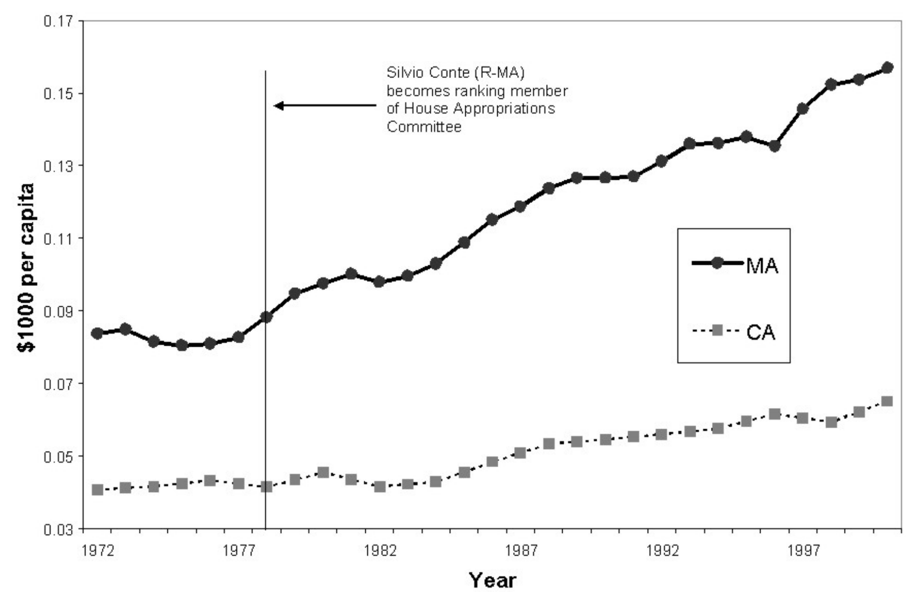

Figure 11

Appropriations Committee Membership & Educational Attainment: Massachusetts Case Study

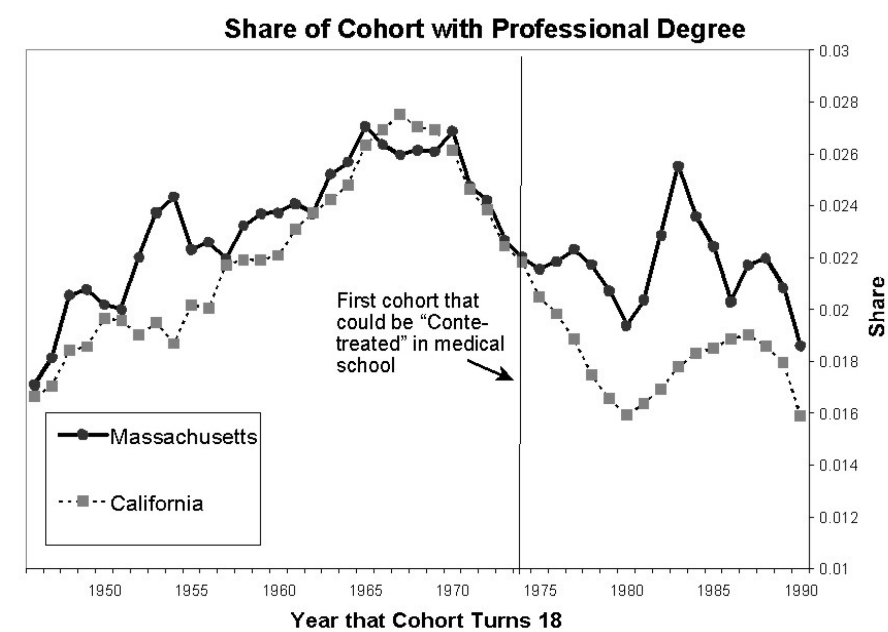

Figure 12

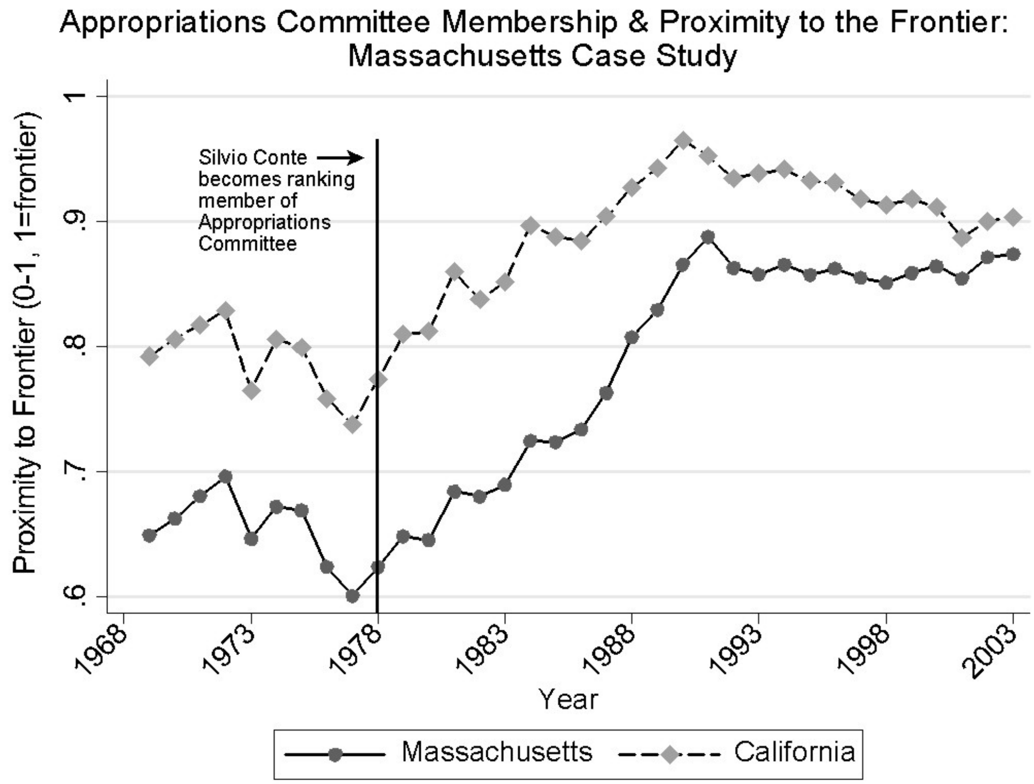

Figure 13

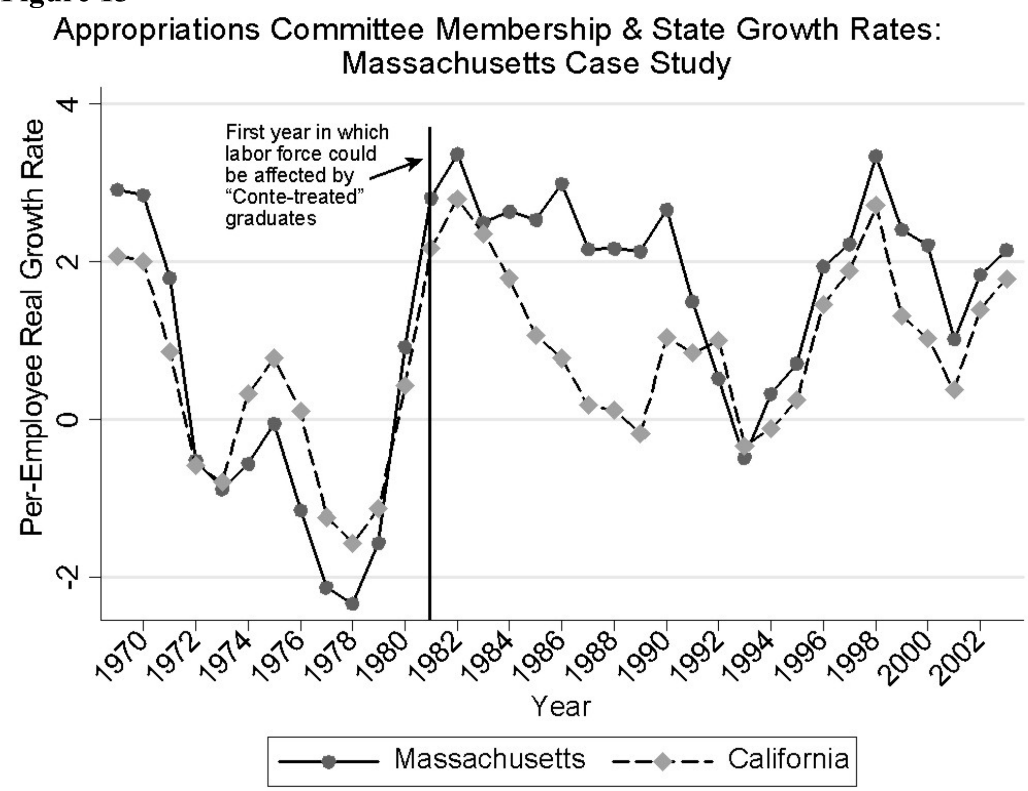

Figure 14

Table 1

Dependent variable: Expenditure on research universities per person in cohort, $2004

	Coefficient	Robust Standard Error
State's members in U.S. House Appropriations Committee	597.20	173.27
State's members in U.S. Senate Appropriations Committee	419.50	113.42
Percent vote for Democratic candidate, last presidential election	-36.27	11.65
Percent vote for third party candidate, last presidential election	-152.50	24.83
Percent vote for Democratic candidates, last Congressional election	-22.49	5.13
Percent vote for third party candidates, last Congressional election	-40.44	8.64
State indicator variables	yes	
Cohort indicator variables	yes	
Census Division linear time trends	yes	
F-statistic joint significance of excluded instruments	10.32	
Overall R-squared	0.96	
Observations (48 states, 1947-1972 birth cohorts)	1248	

All explanatory variables are recorded for period when cohort could naturally attend graduate school: age 22 to 25

Dependent variable: Expenditure on 4-year colleges per person in cohort, $2004

	Coefficient	Robust Standard Error
Education chairman's constituency: number of 2-year college students (thousands)	-28.4999	5.3384
Education chairman's constituency: number of 4-year college students (thousands)	133.7346	22.8493
Education chairman's constituency: percent of employment in finance, insur, r.e.	-4.454351	17.56539
Education chairman's constituency: percent of employment in service industries	3.686299	23.25533
Education chairman's constituency: percent of employment in manufacturing	8.245021	5.661182
Percent of state's upper house who are Democrats	-10.73426	4.376179
Percent of state's lower house who are Democrats	-10.9617	5.91532
State indicator variables	yes	
Cohort indicator variables	yes	
Census Division linear time trends	yes	
F-statistic joint significance of excluded instruments	10.03	
Overall R-squared	0.97	
Observations (50 states, 1947-1972 birth cohorts)	1248	

All explanatory variables are recorded for period when cohort could naturally attend 4-year college: age 18 to 21

Table 1 continued

Dependent variable: Expenditure on 2-year colleges per person in cohort, $2004

	Coefficient	Robust Standard Error
Education chairman's constituency: number of 2-year college students (thousands)	-23.3765	5.5401
Education chairman's constituency: number of 4-year college students (thousands)	134.8356	22.5929
Education chairman's constituency: percent of employment in finance, insur, r.e.	2.42014	15.40859
Education chairman's constituency: percent of employment in service industries	-18.47233	18.24924
Education chairman's constituency: percent of employment in manufacturing	23.98676	6.049594
Percent of state's upper house who are Democrats	3.175413	4.374189
Percent of state's lower house who are Democrats	-14.71945	5.132884
State indicator variables	yes	
Cohort indicator variables	yes	
Census Division linear time trends	yes	
F-statistic joint significance of excluded instruments	10.12	
Overall R-squared	0.96	
Observations (50 states, 1947-1972 birth cohorts)	1248	
All explanatory variables are recorded for period when cohort could naturally attend 2-year college: age 18 to 19		

Dependent variable: Expenditure on elementary & secondary public education per person in cohort, $2004

	Coefficient	Robust Standard Error
State supreme court: percent of justices who are progressive	11.75	8.13
State supreme court: chief justice is progressive	5.51	5.13
Percent of state's upper house who are Democrats	27.65	23.82
Percent of state's lower house who are Democrats	128.87	26.41
State indicator variables	yes	
Cohort indicator variables	yes	
Census Division linear time trends	yes	
F-statistic joint significance of excluded instruments	2.42	
Overall R-squared	0.98	
Observations (50 states, 1947-1972 birth cohorts)	1248	
All explanatory variables are recorded for period when cohort could naturally attend grades K to 12: age 5 to 17		

Table 2

Dependent variable: Research degree holders in cohort per 10,000 in the labor force

	Coefficient	Robust Standard Error
State's members in U.S. House Appropriations Committee	0.485	0.101
State's members in U.S. Senate Appropriations Committee	-0.273	0.188
Percent vote for Democratic candidate, last presidential election	0.020	0.020
Percent vote for third party candidate, last presidential election	0.000	0.034
Percent vote for Democratic candidates, last Congressional election	-0.040	0.011
Percent vote for third party candidates, last Congressional election	-0.009	0.019
State indicator variables	yes	
Cohort indicator variables	yes	
Census Division linear time trends	yes	
F-statistic joint significance of excluded instruments	12.21	
Overall R-squared	0.85	
Observations (48 states, 1947-1972 birth cohorts)	1248	

All explanatory variables are recorded for period when cohort could naturally attend graduate school: age 22 to 25

Dependent variable: Baccalaureate degree holders in cohort per 10,000 in the labor force

	Coefficient	Robust Standard Error
Education chairman's constituency: number of 2-year college students (thousands)	0.039	0.043
Education chairman's constituency: number of 4-year college students (thousands)	0.791	0.297
Education chairman's constituency: percent of employment in finance, insur, r.e.	0.656	0.194
Education chairman's constituency: percent of employment in service industries	-0.030	0.182
Education chairman's constituency: percent of employment in manufacturing	0.069	0.058
Percent of state's upper house who are Democrats	-0.044	0.063
Percent of state's lower house who are Democrats	-0.108	0.069
State indicator variables	yes	
Cohort indicator variables	yes	
Census Division linear time trends	yes	
F-statistic joint significance of excluded instruments	4.92	
Overall R-squared	0.92	
Observations (48 states, 1947-1972 birth cohorts)	1248	

All explanatory variables are recorded for period when cohort could naturally attend 4-year college: age 18 to 21

Table 2 continued
Dependent variable: Persons in cohort with some college per 10,000 in the labor force

	Coefficient	Robust Standard Error
Education chairman's constituency: number of 2-year college students (thousands)	0.135	0.058
Education chairman's constituency: number of 4-year college students (thousands)	-0.133	0.206
Education chairman's constituency: percent of employment in finance, insur, r.e.	1.105	0.250
Education chairman's constituency: percent of employment in service industries	1.419	0.430
Education chairman's constituency: percent of employment in manufacturing	0.243	0.080
Percent of state's upper house who are Democrats	-0.129	0.078
Percent of state's lower house who are Democrats	-0.095	0.089
State indicator variables	yes	
Cohort indicator variables	yes	
Census Division linear time trends	yes	
F-statistic joint significance of excluded instruments	8.14	
Overall R-squared	0.91	
Observations (48 states, 1947-1972 birth cohorts)	1248	

All explanatory variables are recorded for period when cohort could naturally attend 2-year college: age 18 to 19

Table 3
Dependent variable: Annual rate of growth, gross state product per employee in $2004

	Instrument for Education Expenditure Variables (for comparison with previous literature)		Instrument for Education Expenditure Variables & Proximity (preferred estimates)	
	Coefficient	Robust Standard Error	Coefficient	Robust Standard Error
Expenditure (thousands) on research universities per person in cohort	0.075	0.088	0.034	0.095
Expenditure (thousands) on 4-year colleges per person in cohort	**-0.300**	0.135	**-0.283**	0.152
Expenditure (thousands) on 2-year colleges per person in cohort	**0.511**	0.114	**0.650**	0.136
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.125	0.105	-0.105	0.100
Proximity * Expenditure (thousands) on research universities per person in cohort	**0.166**	0.109	**0.234**	0.117
Proximity * Expenditure (thousands) on 4-year colleges per person in cohort	**0.398**	0.126	**0.340**	0.155
Proximity * Expenditure (thousands) on 2-year colleges per person in cohort	**-0.618**	0.123	**-0.705**	0.151
Proximity * Expenditure (thousands) on elem & sec public education per person in cohort	**-0.101**	0.025	**-0.100**	0.020
Proximity to frontier (0-1 index, based on average revenue product of labor)	-1.30	2.73	**-12.24**	3.15
All political variables included in a first-stage equation	yes		yes	
State indicator variables	yes		yes	
Cohort indicator variables	yes		yes	
Census Division linear time trends	yes		yes	
Effects at 0.25 of the frontier (distant states)				
Expenditure (thousands) on research universities per person in cohort	0.116		0.093	
Expenditure (thousands) on 4-year colleges per person in cohort	-0.200		-0.198	
Expenditure (thousands) on 2-year colleges per person in cohort	0.356		0.474	
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.150		-0.130	
Effects at the frontier				
Expenditure (thousands) on research universities per person in cohort	0.240		0.269	
Expenditure (thousands) on 4-year colleges per person in cohort	0.098		0.057	
Expenditure (thousands) on 2-year colleges per person in cohort	-0.107		-0.055	
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.226		-0.206	
Overall R-squared	0.75		0.74	
Observations (48 states, 1947-1972 birth cohorts)	1248		1248	

Notes:
All expenditure-type explanatory variables are in thousands of $2004 and are instrumented with political committee variables (see previous tables)
In variant where proximity is instrumented, it is instrumented with patents in the state.
Dependent variable is recorded for period when cohort would naturally join labor force: ages 26 to 35.
Coefficients in bold typeface are statistically significantly different from zero with 90% confidence at least.

Table 3 continued

Dependent variable: Annual rate of growth, gross state product per employee in $2004		
Results based on spaced cohorts:		
Effects at 0.25 of the frontier (distant states)		
Expenditure (thousands) on research universities per person in cohort	0.135	0.098
Expenditure (thousands) on 4-year colleges per person in cohort	-0.240	-0.224
Expenditure (thousands) on 2-year colleges per person in cohort	0.669	0.735
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.190	-0.144
Effects at the frontier		
Expenditure (thousands) on research universities per person in cohort	0.489	0.535
Expenditure (thousands) on 4-year colleges per person in cohort	0.191	0.109
Expenditure (thousands) on 2-year colleges per person in cohort	-0.029	-0.009
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.258	-0.228

Table 4
Dependent variable: Annual rate of growth, gross state product per employee in $2004

	Instrument for Education Expenditure Variables (for comparison with previous literature)		Instrument for Education Expenditure Variables & Proximity (preferred estimates)	
	Coefficient	Robust Standard Error	Coefficient	Robust Standard Error
Expenditure (thousands) on research universities per person in cohort	0.034	0.056	0.002	0.063
Expenditure (thousands) on 4-year colleges per person in cohort	**-0.096**	0.086	**-0.068**	0.096
Expenditure (thousands) on 2-year colleges per person in cohort	**0.256**	0.073	**0.322**	0.089
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.077	0.057	-0.045	0.055
Proximity * Expenditure (thousands) on research universities per person in cohort	**0.107**	0.069	**0.156**	0.079
Proximity * Expenditure (thousands) on 4-year colleges per person in cohort	**0.185**	0.082	**0.119**	0.099
Proximity * Expenditure (thousands) on 2-year colleges per person in cohort	**-0.321**	0.077	**-0.346**	0.099
Proximity * Expenditure (thousands) on elementary & secondary public education per person in cohort	**-0.059**	0.015	**-0.069**	0.013
Proximity to frontier (0-1 index, based on average revenue product of labor)	-1.72	1.52	**-7.30**	1.98
All political variables included in a first-stage equation	yes		yes	
State indicator variables	yes		yes	
Cohort indicator variables	yes		yes	
Census Division linear time trends	yes		yes	
Effects at 0.25 of the frontier (distant states)				
Expenditure (thousands) on research universities per person in cohort	0.061		0.041	
Expenditure (thousands) on 4-year colleges per person in cohort	-0.050		-0.038	
Expenditure (thousands) on 2-year colleges per person in cohort	0.175		0.236	
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.092		-0.063	
Effects at the frontier				
Expenditure (thousands) on research universities per person in cohort	0.141		0.157	
Expenditure (thousands) on 4-year colleges per person in cohort	0.089		0.051	
Expenditure (thousands) on 2-year colleges per person in cohort	-0.066		-0.024	
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.137		-0.115	
Overall R-squared	0.86		0.85	
Observations (48 states, 1947-1972 birth cohorts)	1248		1248	

Notes:
All expenditure-type explanatory variables are in thousands of $2004 and are instrumented with political committee variables (see previous tables)
In variant with proximity instrumented, it is instrumented with patents from the state.
Dependent variable is recorded for period when cohort would naturally join labor force: ages 26 to 35.
Coefficients in bold typeface are statistically significantly different from zero with 90% confidence at least.

Table 4 continued

Dependent variable: Annual rate of growth, gross state product per employee in $2004

Results based on spaced cohorts:		
Effects at 0.25 of the frontier (distant states)		
Expenditure (thousands) on research universities per person in cohort	0.068	0.053
Expenditure (thousands) on 4-year colleges per person in cohort	-0.080	-0.029
Expenditure (thousands) on 2-year colleges per person in cohort	0.358	0.307
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.117	-0.026
Effects at the frontier		
Expenditure (thousands) on research universities per person in cohort	0.286	0.280
Expenditure (thousands) on 4-year colleges per person in cohort	0.093	0.096
Expenditure (thousands) on 2-year colleges per person in cohort	-0.006	-0.086
Expenditure (thousands) on elementary & secondary public education per person in cohort	-0.160	-0.087

Table 5
Dependent variable: Annual rate of growth, gross state product per employee in $2004

	Instrument for Education Expenditure Variables (for comparison with previous literature)		Instrument for Education Expenditure Variables & Proximity (preferred estimates)	
	Coefficient	Robust Standard Error	Coefficient	Robust Standard Error
Research degree holders in cohort per 10,000 in the labor force	**-0.423**	0.168	**-1.116**	0.172
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.039	0.041	**0.172**	0.044
Persons in cohort with some college per 10,000 in the labor force	0.006	0.016	0.021	0.017
Proximity * Research degree holders in cohort per 10,000 in the labor force	**0.716**	0.187	**1.541**	0.193
Proximity * Baccalaureate degree holders in cohort per 10,000 in the labor force	-0.009	0.038	**-0.214**	0.043
Proximity * Persons in cohort with some college per 10,000 in the labor force	-0.005	0.017	-0.022	0.019
Proximity to frontier (0-1 index, based on average revenue product of labor)	**-14.16**	1.69	-10.76	3.49
All political variables included in a first-stage equation	yes		yes	
State indicator variables	yes		yes	
Cohort indicator variables	yes		yes	
Census Division linear time trends	yes		yes	
Effects at 0.25 of the frontier (distant states)				
Research degree holders in cohort per 10,000 in the labor force	-0.244		-0.731	
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.037		0.119	
Persons in cohort with some college per 10,000 in the labor force	0.005		0.015	
Effects at the frontier				
Research degree holders in cohort per 10,000 in the labor force	0.293		0.425	
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.029		-0.042	
Persons in cohort with some college per 10,000 in the labor force	0.001		-0.001	
Overall R-squared	0.75		0.74	
Observations (48 states, 1947-1972 birth cohorts)	1248		1248	

All education-type explanatory variables are instrumented with political committee variables (see previous tables)
In variant where proximity is instrumented, it is instrumented with patents in the state.
Dependent variable is recorded for period when cohort would naturally join labor force: ages 26 to 35.
Coefficients in bold typeface are statistically significantly different from zero with 90% confidence at least.

Table 5 continued

From regressions with spaced cohorts:		
Effects at 0.25 of the frontier (distant states)		
Research degree holders in cohort per 10,000 in the labor force	-0.238	-0.752
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.074	0.128
Persons in cohort with some college per 10,000 in the labor force	-0.030	-0.034
Effects at the frontier		
Research degree holders in cohort per 10,000 in the labor force	0.171	0.345
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.065	-0.025
Persons in cohort with some college per 10,000 in the labor force	-0.008	0.001

Table 6
Dependent variable: Annual rate of growth, gross state product per employee in $2004

	Instrument for Education Expenditure Variables (for comparison with previous literature)		Instrument for Education Expenditure Variables & Proximity (preferred estimates)	
	Coefficient	Robust Standard Error	Coefficient	Robust Standard Error
Research degree holders in cohort per 10,000 in the labor force	**-0.231**	0.098	**-0.664**	0.102
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.019	0.023	**0.099**	0.025
Persons in cohort with some college per 10,000 in the labor force	0.003	0.010	0.015	0.011
Proximity * Research degree holders in cohort per 10,000 in the labor force	**0.425**	0.112	**0.940**	0.116
Proximity * Baccalaureate degree holders in cohort per 10,000 in the labor force	-0.009	0.021	**-0.132**	0.026
Proximity * Persons in cohort with some college per 10,000 in the labor force	-0.004	0.010	-0.019	0.012
Proximity to frontier (0-1 index, based on average revenue product of labor)	**-9.17**	0.93	**-7.44**	2.03
All political variables included in a first-stage equation	yes		yes	
State indicator variables	yes		yes	
Cohort indicator variables	yes		yes	
Census Division linear time trends	yes		yes	
Effects at 0.25 of the frontier (distant states)				
Research degree holders in cohort per 10,000 in the labor force	-0.124		-0.429	
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.017		0.065	
Persons in cohort with some college per 10,000 in the labor force	0.002		0.010	
Effects at the frontier				
Research degree holders in cohort per 10,000 in the labor force	0.194		0.276	
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.010		-0.034	
Persons in cohort with some college per 10,000 in the labor force	-0.001		-0.004	
Overall R-squared	0.86		0.85	
Observations (48 states, 1947-1972 birth cohorts)	1248		1248	

All education-type explanatory variables are instrumented with political committee variables (see previous tables)
In variant where proximity is instrumented, it is instrumented with patents in the state.
Dependent variable is recorded for period when cohort would naturally join labor force: ages 26 to 35.
Coefficients in bold typeface are statistically significantly different from zero with 90% confidence at least.

Table 6 continued

From regressions with spaced cohorts:		
Effects at 0.25 of the frontier (distant states)		
Research degree holders in cohort per 10,000 in the labor force	-0.128	-0.447
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.034	0.061
Persons in cohort with some college per 10,000 in the labor force	-0.016	0.018
Effects at the frontier		
Research degree holders in cohort per 10,000 in the labor force	0.126	0.244
Baccalaureate degree holders in cohort per 10,000 in the labor force	0.019	-0.037
Persons in cohort with some college per 10,000 in the labor force	0.001	0.007