.The Causal Impact of Education on Economic Growth: Evidence from U.S.

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1 Introduction

Should countries or regions (generically, "states") invest more in education to promote economic growth? Policy makers often assert that if their state spends more on educating its population, growth will increase so much that the state will more than recover its investment. Economists and others have proposed many channels through which education may affect growth--not merely through private returns to individuals' human capital but also a variety of externalities. For highly developed countries, the most frequently discussed channel is education fostering technological innovation, thereby making capital and labor more productive.

Despite the enormous interest in the relationship between education and growth, the evidence is fragile at best. This is for several reasons. First, a state's education investments are non-random. States that are richer, faster growing, or have better institutions probably find it easier to increase their education spending. Thus, there is a distinct possibility that correlations between education investments and growth are due to reverse causality (Bils and Klenow, 2000). Second, owing to the poor availability of direct measures of education investments, researchers are often forced to use crude proxies, such as average years of educational attainment in a state. Average years of education is an outcome that people chose, given their state's investments in education. It depends on returns to education and is, thus, far more prone to endogeneity than is the investment policy. Furthermore, because the average year of education counts an extra year of primary school just the same as a year in a doctoral (Ph.D.) program, average years of education cannot inform us much about the mechanisms that link education investments to growth. It is implausible that making one additional child attend first grade generates technological innovation, and it is equally implausible that adding another physics Ph.D. affects basic social institutions (a mechanism that might link education and growth in developing countries). If we do not know where the

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education investment is taking place, we cannot rule in or rule out mechanisms. Third, researchers most often study education and growth, neglecting intermediating variables that are likely to reveal the mechanisms at work.

We do not claim to solve all these problems in this paper, but we do attempt to address each one. We propose a series of political instruments for different types of education spending. We show that the instruments appear to cause arbitrary variation in states' investments in education, and we argue that it is implausible that the instruments could affect education through channels other than ones we identify. We measure education investments (the actual dollars spent) by type of education, and we construct human capital stocks from the investment flows and depreciation rates based on cognition research. We examine some intermediating variables including migration and patenting. We explore other intermediating variables in other work.[1]

Building on work by Acemoglu, Aghion, and Zilibotti (2003), we develop a multi-state endogenous growth model in which "high brow" education fosters technological innovation and "low brow" education fosters technological imitation (and potentially other growth-enhancing externalities most relevant to developing countries).[2] Our model posits that innovation makes intensive use of highly educated workers while imitation relies more on combining physical capital with less educated labor.

Our model allow workers to migrate, at a cost, towards states that pay higher wages for their skills. Thus, there are at least two reasons why states that are closer to the technological frontier may enjoy different benefits from the same investment in education. A close-to-the-frontier state is more likely to have industries whose growth depends on innovation. Also, its investment in high brow education may generate migration that further increases its highly educated workforce. This may prevent the wages of highly educated workers from rising so much that they choke off innovation.[3] A far-from-the-frontier state may have growth that is more dependent on imitation, so that its low brow education investments generate growth but its high brow investments do not (and may mainly create highly educated out-migrants).

We let the data determine where the split between high brow and low brow education occurs, but it seems safe to say that, if our model is right, graduate

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[1]See Aghion, Dewatripont, Hoxby, Sapir, and Mas-Colell, Economic Policy, 2010.

[2]We are building on a longer literature. The existence of a complementarity between education and innovation was formalized at least as early as Acemoglu (1995) and Redding (1996). Their models do not, however, distinguish between different types of education.

[3]Romer (2000) argues that research and development subsidies that are unaccompanied by an increase in the supply of highly educated labor will raise the wages of existing educated workers but have little effect on innovation and, by extension, growth. Goolsbee (1998) shows that federal research and development spending on aircraft raised wages of physicists and engineers already working in that sector.

education that occurs in research universities should be most growth-enhancing in states that are close to the technological frontier.

1.1 Some Background on Education and Growth

There is ample anecdotal and correlational evidence suggesting that education and economic growth are related, but the evidence points in a variety of directions. For instance, if one favors the education-innovation link, then one might compare Europe and the U.S. in recent years, when Europe has grown more slowly. Sapir (2003) and Camdessus (2004) argue that the slower growth may have been caused by the European Union's relatively meager investment of 1.1 percent of its gross domestic product in higher education, compared to 3 percent in the U.S. One might also look at studies such as Scherer and Hue (1992), who--using data on 221 enterprises from 1970 to 1985--show that enterprises whose executives have a high level of technical education spend more money on research and development that lead to innovations.

If one favors imitation or other channels through which education affects growth, one might note that, in the thirty years after World War II, Europe grew faster than the U.S. even though it invested mainly in 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. Examining cross-country correlations, Krueger and Lindahl (2001) conclude that "[overall,] education [is] statistically significantly and positively associated with subsequent growth only for the countries with the lowest education."

Clearly, the education-growth relationship is not so simple that one can compute average years of education in a state and confidently predict growth. We believe our model clarifies matters. It explains why higher education may be more growth-enhancing in the U.S. or Europe today than in their own past or than in developing countries. It explains why average years of education is not a sufficient statistic to predict growth: two states with the same average years and the same distance from the technological frontier will grow at different rates if the composition (primary, secondary, tertiary) of their education investments differs.

1.2 Theoretical Precursors

It is impossible to do justice to existing models of education and growth in a few sentences, but we must draw attention to some key precursors. Early on, Nelson and Phelps (1966) argued that a more educated labor force would imitate frontier technology faster. The further a state was from the frontier, the greater the benefits of this catch-up. Benhabib and Spiegal (1994) expanded on their work, arguing that a more educated labor force would also innovate faster. Lucas (1988) and Mankiw, Romer, and Weil (1992) observed that the accumulation of human capital could increase the productivity of other factors and thereby raise growth.[4] Notice that, at this point, we have separate arguments for why the stock of human capital, the rate of accumulation of human capital, and distance to the technological frontier should affect growth. Our model coherently integrates all these strands, is the first to distinguish between types of education spending, and is the first to consider the interplay between the composition of spending and a state's distance from the frontier.

Acemoglu, Aghion, and Zilibotti (2003)'s model and our model do not provide the only explanation for why higher education might be more growth-enhancing in some states than in others. Suppose that there are strategic complementarities ("O-ring" complementarities) among highly educated workers. Then, states in which highly educated workers make up a large share of the labor force would get more growth out of investing in higher education than states in which highly educated workers make up only a small share. The strategic complementarity model does not rely on distance to the technological frontier or the nature of technical change (the imitation/innovation distinction). There are two matters that the strategic complementarity model does not explain. First, it is unclear what the complementaries are if they do not correspond to something like innovation. What exactly are the highly educated workers doing together (that is so sensitive to their being highly educated) if it does not involve changing the nature of production? Second, a model entirely based on skill complementarities does not predict convergence in growth rates between frontier and far-from-frontier states. Yet, there is ample evidence that states' growth rates converge.[5]

1.3 Empirical Precursors and a Preview of Our Empirical Strategy

Similarly, it is impossible to do justice to the wide array of existing empirical analysis of education and growth. Suffice it to say that, while we have learned a great deal from then, we are also persuaded by the argument of Bils and Klenow (2000) that existing studies tend to establish correlations, but tend not to establish the direction of causation.

To illustrate the problem, let us pick on one of our own papers rather than that of someone else: Vandenbussche, Aghion, and Meghir (2005, hereafter VAM). VAM employ panel data on 22 OECD countries every five years between 1960 and 2000 (122 observations). Their ability to identify causal effects is limited both by the small size of their dataset and their instrument: education spending lagged ten years. Lagged spending is problematic because the omitted variables about which we are worried are all highly correlated over

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[4]In the Lucas and Mankiw, Romer, and Weil models, a state's rate of growth depends on the rate of accumulation of human capital. Ha and Howitt (2005) point out that such models are hard to reconcile with a state like that U.S., which has sustained growth despite a slowing of its rate of accumulation of human capital.

[5]See Barro and Sala-I-Martin (1991) and the many papers that cite it.

time within a country. Thus, instrumenting with lagged spending does not overcome biases caused by omitted variables such as institutions. VAM do try including both time and country fixed effects, but, when they do, the estimated relationship between education and growth disappears, suggesting that there was not much arbitrary spending variation in the data.

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. Such comparisons are inherently awkward because we are left wondering why, if the two states are so similar, they pursue different investments. We would like to be assured that their policies differ for arbitrary reasons. That is, we seek instrumental variables that cause a state's investment in education to change in a way that uncorrelated with fundamental changes in its growth prospects.

Our instruments depend on the details of appointments to committees in legislatures. All the instruments have the same basic logic. When he is able to do it, a politician needs to deliver payback to his constituents in return for their support. Generally, politicians cannot deliver payback in cash but can deliver specific investments--for instance, building a new school for a research university. The process we exploit is that, when a vacancy arises on an committee that controls expenditure, the state that is "first in line" tends to get the seat, thus enabling its legislator to deliver a positive shock to spending in his state's educational institutions. Because determining which state is "first in line" depends on fairly abstruse interactions in legislators' political careers (we explain this), a state's getting a member appointed to the committee does not simply reflect its contemporary political importance or other factors likely to be correlated with its growth prospects. In fact, our instruments work even though we fully control for variables indicative of contemporary partisan politics as well as time fixed effects, state fixed effects, and Census division-specific time trends. Below, we offer detailed explanations of our instruments and show that they predict shocks to educational investments that are plausibly exogenous, conditional on the variables for which we control.

We use data from American states partly because such data allow us to measure education investments accurately and partly because the U.S. is the setting in which our instruments work. When we first settled on using cross-U.S. state data, we thought that migration across states would be a nuisance. Instead, migration turns out to be a revealing intermediating variable, as we show.

Our cross-state focus within the U.S. state makes our paper related to Bound, Groen, Kezdi, and Turner (2004) and Strathman (1994). Both studies show that migration plays an intermediating role between the educational investment of a state and the stock of educated workers with which it ends up. Our paper is also related to studies of how universities affect innovation in the geographic area immediate around them: Adams (2002); Andersson, Quigley, and Wilhelmsson (2004); Anselin, Varga, and Acs (1997); Fischer, Mafred, and Varga (2003); Florax (1992); Jaffe (1989); and Varga (1998).

2 A Multi-State Endogenous Growth Model

2.1 The 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

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

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

$$\hat{U}_t \equiv u_{m,t} + u_{n,t} \quad (4)$$

which represents total unskilled labor employed in productivity improvement and

$$\hat{S}_t \equiv s_{m,t} + s_{n,t} \quad (5)$$

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

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[6]

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

[6] 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 A 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

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

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 $\Delta > 1$[7]. The dotted line (F) represents the factor intensity in final good production. Below the curve (P)-(P)[8], 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

[7] 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).

[8] 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 Our Main Prediction: The Effect of Education on Growth

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.[9]

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

[9] Allowing for the migration of unskilled workers would not alter the qualitative results. To see this, suppose that we also allow unskilled workers to migrate. When skilled workers migrate toward the states close to the frontier, they raise the marginal productivity of the unskilled workers who are in states close to the frontier and reduce the marginal productivity of unskilled workers in states far from the frontier. If the unskilled workers who have been "abandoned" can migrate as well, then benefit of migrating will increase for the skilled workers. Hence, allowing migration of the unskilled reinforces the positive interaction between proximity to the frontier and education.

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 Education on Growth, with Migration

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)*

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

(b)

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

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 term $h(\alpha)^{-\varphi}$ in (14) and for which we already provided an intuition in the previous section. The second is a migration effect captured by the term $(1-\mu^*(\alpha,U,S)$ 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 $-S\cdot(\partial\mu^*(\alpha,U,S)/\partial S)$. 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 innovation 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.[6]

4 From Theory to Empirics

The model has a few key predictions: (i) the economy's growth should be increasing in exogenous increases in low brow human capital--the more so when the economy is far from the technological frontier; (ii) the economy's growth should be increasing in exogenous increases in high brow human capital--the more so when the economy is close to the technological frontier; (iii) as regards growth, migration will exacerbate the complementarity between the innovation-proneness of human capital and proximity to technological frontier.

To test the model, we need measures of growth, measures of technology, and measures of the human capital stock differentiated by type. In this section, we discuss each of these requirements. We also need exogenous

[6]As the number of highly educated workers migrating to a frontier state increases, there may be congestion arising, for example, from the limited supply of land. This may generate rising housing prices in close-to-the-frontier states to which skilled workers are migrating. The higher cost of living in these states will also drive up wages of unskilled service workers (such as hairdressers and janitors) who are needed by the skilled workers. These phenomena, which have been explored by Taylor et al (2003) will dampen but not reverse the migration effect. These phenomena do not affect the magnitude of the reallocation effect. Our estimates will, of course, reflect the "dampening" of the effect, although we have not included such phenomena in the model for the sake of clarity.

variation in the human capital stock--that is, we need valid instruments. We defer this issue to Section 5.

4.1 The Estimating Equation

Real economies vary greatly in scale and not merely because of differences in their endowments of high brow and low brow human capital: they also have endowments of natural resources, physical capital, and amenities. The model abstracts from these issues, but--of course--our estimating equation cannot. We make two reasonable modifications to adapt the model for estimation. First, we measure human capital stocks and growth on a per capita basis. Among methods of rescaling economies to make them comparable, we have found that this one is by far the most acceptable to audiences. Second, we control for a variety of covariates that intended to make all else equal. Because instruments are only valid or invalid conditional on the covariates, we defer the discussion of the covariates until we have described the instruments.

With these caveats, an estimating equation that tests the main implications of the model is:

$$g_{jt}=\kappa_0+\kappa_1 S_{jt}+\kappa_2 U_{jt}+\kappa_3 S_{jt}\cdot\alpha_{jt}+\kappa_4 U_{jt}\cdot a_{jt}+\ldots+\varepsilon_{jt}$$

where g_{jt} is growth, S_{jt} is high brow human capital, U_{jt} is low brow human capital, and α_{jc} is proximity to the technological frontier. Recall that $\alpha_{jc}=1$ for a state at the frontier. In the equation, the ellipses represent the aforementioned covariates, j indexes states, t indexes years, and d indexes Census divisions.

κ_1 and κ_2 reflect the effect on growth of, respectively, high brow and low brow human capital in a state that is far from the technological frontier. $\kappa_1+\kappa_3$ and $\kappa_2+\kappa_4$ reflect the effect on growth of investments in, respectively, high brow human capital and low brow human capital in a state that is at the technological frontier. Since we impose no restrictions on the values of the parameters, we may find that $\kappa_3=0$, $\kappa_4=0$, and $\kappa_1=\kappa_2$. In this case, the equation collapses to a specification often used in the empirical literature on education and growth, namely:

$$g_{jt}=\kappa_0+\kappa_1(S_{jt}+U_{jt})+\ldots$$

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 actually allow human capital to come in four different types: research type education (doctoral programs including medicine and J.D.s), four-year college type education (including masters degree programs), two-year college type education (lower postsecondary programs), and primary and secondary type.

4.2 Measuring Growth

Our preferred measures of economic growth are the annual growth in real per capita personal income and per capita gross state product (GSP).

4.3 Measuring Human Capital

One key contribution of this paper is that we measure human capital stocks more accurately and--we believe--more thoughtfully than most of the previous literature on education and growth. The previous literature generally uses average educational attainment among working-age adults as its measure of human capital. This measure is so familiar that has somehow come to be seen as the logical measure as well. In fact, it imposes restrictions that are not at all appealing. We mention these restrictions as we describe our preferred measures of human capital.

Economists normally construct capital stocks by aggregating previous years' investment, depreciated according to a schedule that corresponds as closely as possible to true economic depreciation. This is what we attempt to do to form our preferred measures of human capital. Specifically, we start with the educational investments that are "released" each year onto the job market. For instance, each year a cohort of people with 12 years of primary and secondary education is released onto the market, and the total investment in their schooling is the school spending they experienced over the previous 12 years. Similarly, each year a cohort of people with 2-year college degrees is released onto the market, and the investment in their college-level schooling (that is, beyond secondary school) is the college spending they experienced at 2-year colleges over the previous 2 years. And so on for 4-year college education and research-type education. (We assume that research-type degrees take 4 years on average beyond the baccalaureate degree. The results are not sensitive to our assuming 5 years instead.)

At this point, we have the investment entering the market in each year, but we have not yet aggregated across years to form the capital stock. Nevertheless, what we have done is already an improvement: monetary investments in schooling have several advantages over attainment. First, they accurately register the difference in spending between various levels of education. For instance, more is spent on a year of education for a doctoral student in chemistry than for a year of education for a kindergartner. Second, monetary investments register differences in spending (for the same grade) between states. A year in a resource-rich school is not the same as a year in a resource-poor school. Third and most important, the spending-based measure records what policy actually affects: spending. Educational attainment, in contrast, is far more endogenous. After all, people can refuse to take up educational opportunities that are offered to them and people may be particularly likely to ignore opportunities if they are poorly aligned with the demand for workers in their 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 jobs for such workers are located.

What we must do to aggregate the education investments across years is apply a reasonable depreciation schedule. There are two reasons why human capital investments depreciate: obsolescence and forgetting. For instance, the computer science knowledge that someone acquired 20 years ago may simply be obsolete. Also, knowledge and skills tend to atrophy if a person does not re-invest in them. For instance, a person may forget a foreign language, how to solve algebraic problems, or how to write a persuasive essay if he does not routinely reinvest in maintenance. Unfortunately, a universally accepted, empirically based depreciation schedule for human capital does not exist. However, cognitive scientists have carefully studied knowledge depreciation over a variety of domains: high school level material, college-level mathematics, science, social science, and humanities subjects; research-level knowledge of science, and so on. The consensus in the literature is that knowledge acquired in school depreciates quickly over the first several years so that something on the order of 20 percent is retained by the end of a decade. However, what is still retained at that point then depreciates only very slowly until a person reaches retirement age, at which point knowledge acquired in school depreciates very swiftly toward zero.[7] The economic depreciation schedule is not only a matter of knowledge depreciation, however. Cognitive scientists' studies do not account for knowledge obsolescence, which would tend to increase depreciation rates. They also do not account for the fact that some human capital acquired in school is not knowledge but skills that are not readily testable. Some such skills may depreciate faster than readily testable knowledge; other such skills may depreciate more slowly.

Given what is known, our preferred schedule has education investments depreciate at a uniform rate over the first decade until 20 percent of the investment remains. Then the remaining investment depreciates at (another) uniform rate for 35 years until 10 percent of the original investment remains. After 35 years, 0 percent of the original investment remains. We show specification tests where we vary the depreciation rate in the first decade, within a range supported by the cognitive science literature. Changing the depreciation rate used after the first decade has, unsurprisingly, virtually no effect on the results, so we do not show specification tests related to that.

Note that using average educational attainment among adults as a measure of the human capital stock corresponds to the assumption that education acquired in school does not depreciate at all until retirement, when it becomes zero. This assumption receives little or no support from the scientific evidence. More generally, we were surprised by how little economists, including ourselves, had analyzed depreciation of human capital acquired in school. Empirical studies often conflate school-derived human

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[7] Unsurprisingly, the depreciation rate depends somewhat on the field of knowledge. For good reviews of the relevant cognitive science literature, see Conway, Cohen, and Stanhope (1992) and Custers (2010). See also Bahrick (1992).

capital with post-schooling investments in human capital. In a few applications, such conflation does not matter. In our application, however, it does: post-schooling investments are a function of how a person employs his school-derived human capital in the economy. These employment patterns are closely related to what we are trying to explain.[8]

4.4 Measuring Proximity to the Frontier

A state's proximity to the frontier is endogenous to its education investments, although in a slow-changing way because a state's technology cannot be replaced overnight. We therefore take two actions to ensure that our measure of proximity is not plagued by endogeneity. First, we measure it at the very beginning of the period we study, when the cohorts we study are not nearly old enough for their education to have affected technology directly. Second, we use a measure of proximity based on patenting. Alternative measures of proximity (which work quite similarly in practice) can be based on measures of labor productivity in the state. However, we are concerned that, because productivity measures are computed using some of the same data that we use for our dependent variables, our estimates might suffer from the propagation of measurement error (measurement error that occurs in both the dependent and an independent variable).

Patents are indicators of technology because states that produce numerous inventive patents (called "utility patents") are likely to be at the technological frontier. This is because frontier technologies are constantly being refined, thereby generating patents. In contrast, old technologies are so well known that they produce little patenting activity.[9]

To be precise, our measure of proximity to the frontier is a state's number of inventive patents relative to the size of its economy in 1963. We standardize this measure by subtracting the typical minimum of the measure among states and then dividing by the maximum among states. Thus, 1 represents a state at the frontier and zero represents the state furthest from the frontier in 1963.

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[8] A related point is that Mincerian wage regressions, in which ln(earnings) are a (typically quadratic) function of education and experience, should be interpreted somewhat differently than they usually are. In these regressions, which do a fair job of fitting the data, education should probably be interpreted as the original investment in schooling plus the typical investment in maintenance and improvement of schooling-type human capital. For instance, an engineer who routinely invests in learning new engineering techniques and models is not merely using his school-derived human capital to earn wages. He is also using human capital acquired since leaving school. Another related point is that the decay in earnings power associated with non-employment may be due as much to failure to invest in education maintenance as to depreciation of work-specific skills.

[9]We record utility 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.

It is reassuring that our measure produces few surprises. Close-to-the-frontier states include New Jersey, Massachusetts, Pennsylvania, and Connecticut. Far-from-the-frontier states include Mississippi, Arkansas, the Dakotas, and Georgia.

4.5 Distinguishing the Effects of Migration

The estimating equation and measures we have described so far generates results that include the effects of education on migration. That is, if Mississippi's investment in high brow human capital causes people to migrate to states closer to the frontier, the migration-induced reduction in Mississippi's growth (relative to what it would have been had the people stayed) is reflected in the coefficients. Analogously, if Massachusetts ' investment in high brow human capital causes people to it from states further from the frontier, the migration-induced increase in Massachusetts' growth is reflected in the coefficients.

In order to distinguish the effects of migration, we change our measure of growth in such a way that the coefficients no longer reflect migration. To see this, suppose that 10 percent of the human capital stock produced in Mississippi now lives in Massachusetts (that is, it is associated with people who now live in Massachusetts). Suppose that the other 90 percent of the human capital stock produced in Mississippi still lives in Mississippi. Create a growth rate for Mississippi-produced human capital based on a weighted average of Massachusetts' growth rate (10 percent weight) and Mississippi's growth rate (90 percent weight). If we put growth rates computed in this way into our estimating equation, we un-do migration so far as the coefficients are concerned. Of course, computing the growth rates is more complicated because there is migration to all 50 states and flows along any given route (for instance, Massachusetts-Mississippi) are not unidirectional. Nevertheless, by using growth measures computed according to the procedure outlined above, we attempt to estimate effects purged of migration. The estimated effect of migration is then the difference between our two sets of estimated coefficients.

5 Instruments for Education Investments

Our model suggests that states' educational investments and growth differ mainly because of exogenous differences in their technology. Unfortunately, much of the variation that we observe in education investments is endogenous or correlated with omitted variables that could cause a state simultaneously to grow quickly and invest in education.

In order to test the effect of education on growth, we need instrumental variables that generate variation in education investments that is credibly arbitrary conditional on a state's observed characteristics. The conditioning is of non-trivial importance. We can and do control for contemporary politics; 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 Census divisions, which eliminate regional trajectories due to, say, a shared industrial history. We can also control for the main other form that political payback takes in the U.S.: spending on highways and similar infrastructure.

Our proposed instrumental variables all are based on the idea that appointment to certain political committees allows a legislator to deliver payback to his constituents in the form of specific education investments. These specific investment are disproportionately in the constituents' self-interests and need not represent the broader interests of the society that the legislature is intended to serve.

Since we are interested in different types of education investment, we need instruments for each type. Here, the specificity of payback is helpful. We show that membership on federal committees generates shocks to research university spending. We also show that membership on state committees generates shocks to the type of education institution (four-year college or two-year college) that is present in the legislator's constituency.

It is important to understand that our instruments come from the internal details of politics, not from general political tendencies. This is why the instruments work even though we control for numerous measures of contemporary partisan politics. We would not want instruments that mainly reflected contemporary partisan politics because they would likely be endogenous to a state's economic experience. For instance, in recent U.S. elections, "old industry" states' politics are influenced by industrial unions' opposition to unconstrained international trade. Such politics probably generate votes for the Democratic party, and such voting would be endogenous to the state' growth prospects.

5.1 Instrumental Variables for Research-Type Education

It is easiest to illustrate how the instruments work by starting with federal politics which--it will turn out--affect research-type education, the epitome of high brow education.

In the U.S. Senate and House of Representatives, the Appropriations Committees control the allocation of federal funds to projects. Some funds for research universities are awarded through a competitive process whereby the Appropriations Committees simply allocate a lump sum to an agency like the National Science Foundation and have it disburse the money using merit-based competitions. However, the Appropriations Committees can also propose that individual projects be funded without regard to merit or larger policy considerations. It is well known that such individual projects are the main route by which congressmen deliver payback to their constituents. It is precisely the opportunity to fund such projects that makes a seat on the Appropriations Committee so valuable.

Research universities are important channels for pay back because they are geographically specific to a legislator's constituency. In contrast, many forms of spending are formula-based and are, therefore, inefficient ways to channel spending to one's constituents. For instance, a congressman may have numerous Medicare recipients (elderly people who rely on the federally-funded medical plan), but it would not be efficient for him to pay them back by raising Medicare spending. This is because he could only increase the generosity of the Medicare formula, and most of the increased generosity would go to people outside his constituency. There are only a few ways that legislators can send large amounts of payback to their constituency and only their constituency. One is funding for a research university. Another is funding for a particular highway, bridge, or similar infrastructure project located in the constituency. While a legislator can also direct money to an array of other types of projects, these do not add up to much money compared to research and infrastructure funding.[10] Below, we provide a few case studies of particular legislators who, upon becoming Appropriations committee members, directed billions of dollars to research universities in their constituencies, building laboratories, medical schools, and other research facilities.

It is important to note that federal legislators do not have an equivalent means of narrowly directing substantial federal funds to their constituency's primary schools, secondary schools, or non-research-oriented postsecondary institutions. Federal funds for these types of education are allocated through formulas. For instance, the vast majority of federal funding for primary and secondary schools is allocated by formulas based on measures of students' poverty, limited English proficiency, and disability.[11] The vast majority of federal funding for postsecondary training and teaching colleges is allocated through the Pell Grant, Guaranteed Student Loans, and other programs and tax expenditures that use formulas based on a student's family income. In short, if a federal legislator wants to use his membership on the Appropriations Committee to deliver payback, he will end up directing funds toward research-type education, even if his state would prefer to invest in lower-brow education.

Because a seat on the Appropriations Committee is so valuable, a legislator who has one does not give it up voluntarily. Both houses of Congress respect an incumbent committee member's right to continue on this committee. Thus, once on, a legislator tends to stay on the committee for several years, and nearly all vacancies arise because a member has died in office or retired from legislative political life (through old age or being appointed, say, to the President's cabinet). A vacancy sets off a complex political process that generates our instruments. Although the process is not written down formally, political scientists and our own work have determined the implicit process to be roughly as follows.

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[10]In a limited number of constituencies, spending on the local military base is another important channel for sending payback to the constituency and only a constituency.
[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 trivial share of spending on U.S. primary and secondary education: less than one-tenth of one percent.

When a vacancy arises, each party considers the resulting state composition of the committee within the party and whether that composition matches the state composition of its party members in its house of Congress. Thus, if when the vacancy occurs, Florida's Democratic legislators occupy 5 percent of the Democratic committee places but Florida Democrats make up 10 percent of the Democrats in the house, Florida has a representation gap of 5 percent. The state with the largest gap is very likely to fill the vacancy, and political custom is such that the most senior, eligible legislator from the state is very likely to be the new committee member. To be eligible, a legislator must not be on the committee already or be occupying a high ranking seat on one of a couple of other "exclusive" committees. (See the Appendix for detail.)

Now, if vacancies arose very regularly (for instance, if legislators never served more than one term), then the state and party composition of the Appropriations Committee would always be a mirror image of the Congress. But, in fact, incumbent legislators (especially multi-term incumbents) usually win elections in the U.S. because campaign finance, the drawing of election districts, and other phenomena make them likely to defeat challengers in an election. Since an incumbent legislator keeps his seat on the committee, the committee can become imbalanced over time. For instance, consider Massachusetts, which shifted from being a bi-partisan state to a mostly Democratic state. It had a couple of incumbent Republican legislators on the Appropriations Committee. As its party preferences shifted, these incumbents kept their committee seats even while the Democratic party--through the process described above--was obliged to appoint Massachusetts Democrats to the committee. Thus, Massachusetts ended up with much more representation on the Appropriations committee than the state's population warranted. Of course, for every lucky state like Massachusetts that is in the right place at the right time and becomes over-represented, there is an unlucky state that becomes under-represented.

The bottom line is that the process of vacancy-filling is complex because it depends in a highly path-dependent way on every state's political history, not just on the current state of affairs in the state whose legislator ends up filling the vacancy. The enormous path dependence in the process creates strange lotteries where, for instance, Massachusetts is lucky and another state is unlucky. Thus, our instruments--which are the interaction between the arrival of a eligible vacancy and the within-party state gap in committee membership at the moment the vacancy arises--generate variation in states' representation on the Appropriations Committees and, consequently, variation in federal spending. It is not plausible that, through some channel other than federal spending, these instruments directly affect a state's growth prospects. Because we know that federal highway-type spending may also be positively shocked when a state gets a member on the Appropriations Committee, we control for that variable.

To be precise, to compute our instruments for research spending, we compute the likelihood that each individual congressmen is appointed to the

Appropriations Committee on each possible date. We actually do this using a regression with numerous interaction terms, but the computation is quite easy to describe in words. The likelihood is zero is there is no vacancy or if the congressmen is an incumbent member of the Committee.[12] It is approximately zero if the congressmen is a high ranking member of another exclusive committee.[13] After ruling these congressmen out, the remaining legislators are ordered according to the within-party representation gap that their state has at the moment the vacancy arises. Within their state and between states with the same representation gap, legislators are ordered by seniority. The legislator who is first in line has the highest probability of being appointed, and so on.

We then compute a few aggregates of the probabilities by state at each point in time: the maximum probability of appointment enjoyed by any of the state's legislators in the house in question, the mean probability of appointment enjoyed by the state's legislators in the house in question, and the sum of the probabilities of appointment enjoyed by the state's legislators in the house in question. In practice, the most powerful instrument for Senate appointments is the maximum probability (but any of the aggregates works well) and the most powerful instrument for House appointments is the mean probability. All are valid instruments.

Below, we show that these instruments predict appointment to the Appropriations Committee and the spending of research universities in the state. In our case studies, we narrate a few examples of how an appointment can affect spending. For now, examine Figure 1, which illustrates the connection between appropriations committee membership and federal spending in a simple way. The vertical axis records federal spending on research universities per person in 2004 dollars. (All dollars hereafter are 2004 dollars, based on the Consumer Price Index-U.) The horizontal axis records the number of members on the U.S. House appropriations committee. Each observation is a particular year in a particular state, and both the spending and membership variables are residuals from which state effects, year effects, and Census division time trends have already been partialed out. Thus, the relationship shown is above and beyond patterns whereby certain states are

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[12]Vacancies are party-specific. If a vacancy arises in the middle of a Congress, due to death for instance, then it is filled by a legislator of the same party as the legislator who left. If a vacancy arises at the changeover between two Congresses, then the seat is allocated between the parties based on their overall representation in their house (which will changed if a recent election swung party representation significantly), compared to their overall representation in the house. We found it straightforward to say to which party each vacant seat would be allocated.

[13]The exclusive committees are listed in the rules of each house of Congress, and members may not sit on two of them. Legislators rarely move from one to another because, if they did, they would have give ranking seat on one important committee to get the most junior seat on another. See the Data Appendix.

routinely powerful politically or whereby certain states' political power is gradually increasing.

Figure 1 Here

The figure shows that, when the state-year has an unusually high degree of membership on the House appropriations committee, spending on research universities is unusually high. And vice versa. Our formal analysis exploits this relationship but includes additional controls. The typical shock to research university spending last 6 to 8 years.

For much of the thinking behind our instruments, we acknowledge our debt to previous economists and political scientists, especially Roberts (1990), Greenberg (2001), Feller (2002), and Payne (2003).[14]

5.2 Instrumental Variables for Four-Year and Two-Year College Education

To get exogenous shocks in funding for four-year (non-research-type) and two-year colleges, we turn to the politics of state legislatures since it is they that largely determine government funding for such institutions. We again exploit the arrival of vacancies on legislative committees--this time the chairmanships of the states' senate Appropriations and senate Education committees.[15] We focus on senates and chairmanships because the typical state legislator has a short political career and little influence. For instance, lower houses' members turn over with such frequency that they and their committees largely reflect contemporary partisan politics. For our instruments, we need the arbitrariness introduced by the path-dependent interactions between legislators with longer careers in politics, and such legislators are typically state senators with some probability of appointment to a chairmanship.

We cannot do exactly what we did at the federal level at the state level. This is because state chairmanships arise in a more haphazard way, they are filled in a more arbitrary way from the likely senators, and state legislatures do not have the data that would allow us to figure out the entire network of committee memberships going to the 1950s. Indeed, it was challenging to get

[14]Our understanding of the process of committee assignments owes much to Masters (1961), Bullock and Sprague (1969), Gawthrop (1966), Rohde and Shepsle (1973), Gertzog (1976), Munger (1988), Sinclair (1988), Hedlund (1989), Hedlund and Patterson (1992), Francis (1995), Stewart and Groseclose (1999), and Frisch and Kelly (2004). However, we reprocessed all of the raw data for ourselves (see Appendix) and reformulated the empirical procedure through which legislators are appointed to committees. The aforementioned literature provides ideas about the procedure, but we found that some of the ideas were empirically invalid and other ideas were valid but had weak explanatory power. The process we describe is the one with by far the most explanatory power, and it is therefore the most likely to be correct, as an empirical matter.

[15]These are the two committees that most influence state allocations to individual four-year and two-year colleges.

data on the chairmen alone. Political scientists find that chairmanships in state senates are distributed fairly arbitrarily among members who have high seniority. Unlike federal members of the Appropriations committee, state senators of the chairmanship class are shifted between committees at intervals, purportedly to "spread the wealth" and to keep them from establishing power bases separate from the party leadership. See Pitney (1982), Francis (1985), Squire (1988), Hedlund (1989), and Hedlund and Patterson (1992).

We rely on changes in the higher education institutions that are located in the chairman's constituency when that chairmanship changes hands. This is best illustrated with an example. Suppose that state senator X whose constituency included a public four-year college retires from chairing his senate's appropriations or education committee. Suppose that he is replaced by senator Y whose constituency includes a public two-year college. Empirically, we see state funding shift from four-year colleges to two-year colleges. The next time a vacancy arises, we might see a shift away from college education altogether and toward primary and secondary education or entirely different spending areas--this outcome is likely if the new chairman's constituency includes no colleges that can be direct beneficiaries of political largesse. We do not claim that it is random that a senator is made a committee chairman at all, but we think that the timing of changes in the identity of colleges located in the chairman's constituency is arbitrary.

In short, to generate instruments for state spending on four-year and two-year colleges, we identify the chairmen of each state's Appropriations and Education committees at each point in time and associate them with the postsecondary institutions in their constituencies. We then compute the number of enrolled students at each type of college (public four-year, private four-year, public two-year, private two-year) in the constituencies. We use the 1980 enrollment of colleges for all cohorts.[16] Thus, the instruments change only because the chairman changes. They do not reflect the ongoing success of a college, something that could be endogenous to a chairman's generosity with government funding. The typical shock to four-year or two-year college spending lasts 6 to 8 years because this is the length of a typical state senate chairmanship.

Readers interested in the exact mechanisms by which chairmen funnel money to institutions in their constituencies will want to know that public colleges are typically individual line items in the state's budget. State grants to postsecondary institutions pay for both capital expenditures (campus buildings) and operating costs. If a state senator wants funds to go to the college in his constituency and only his constituency, capital expenditures are the most likely route. However, since the institutions are usually eager for operating funds, we often see chairmen direct operating funds to all colleges of

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[16]1980 is the earliest year for which the data on two-year colleges is very complete. However, the results would not more than trivially affected if we to use data from the earliest year available, which is 1967.

the same type as the college in their constituencies. This is not an inefficient way to direct funds because the typical state has a few or several, not dozens, of colleges of a particular type.

We are confident that changes in the identity of colleges in the chairmen's constituencies are credible instruments, in part because they are powerful even though we control for the industrial composition and socio-demographics of the chairmen's constituencies. We also control for several measures of contemporary state partisan politics.

5.3 A Difference between the Federal and State "Experiments"

The "experiments" generated by our federal and state political instruments are not completely parallel. Federal spending increases are paid for by all U.S. states, not just the state that benefits. Of course, we expect that every state will eventually pay for its share of federal allocations to research universities, but when a shock occurs, most of the funding is coming from other states' tax payments.

In contrast, when a state senate chairman directs funds to four-year or two-year colleges, he is directing them away from some other use (including private consumption) in his state. Thus, it is quite easy to imagine such education funding shocks having a negative effect on the state's growth: the alternative use of the money could have been more productive. The four-year and two-year college spending experiments exemplify what happens to a state when it shifts money towards education, holding total resources constant.

The experiments in research-type education do not hold total resources constant. They nearly always constitute a short-term infusion of money that will be recovered by the other states when the legislator from the state in question has lost the appointment that allowed him to be so generous.

5.4 Instrumental Variables for Primary and Secondary School Spending

We do not have good instruments for primary and secondary school spending in a state. We therefore control for it but cannot interpret its coefficients in a causal way.[17]

[17] We attempted to construct instruments for primary and secondary education in several ways. Our most successful instruments derive from state lawsuits that affect primary and secondary school spending. Plaintiffs in such lawsuits invoke state constitutions to alter the distribution, and sometimes the level, of public school spending. We find that the preferences of individual judges who try the lawsuits have an important effect on the outcomes and that there is some arbitrariness in the assignment of judges to the cases. However, the instruments we generate through this procedure have much more effect on the distribution of spending within a state (how a given amount of spending is allocated between districts that serve poorer and richer children) than the level of spending in a state.

5.5 The Timing of the Instruments

The instrumental variables should be timed so that they correspond to the years in which educational investments were made. The question that arises is how much of a lag to leave between a committee member's appointment and actual appropriations arriving at the educational institutions. The empirical evidence suggests that two years is the normal lag. This makes sense because 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. For instance, if a newly appointed House Appropriations member is going to show an institution in his district that he can direct funds toward it, he will try to do it within two years of the appointment. Thus, not only does two years appear to be the appropriate lag, but we also believe that it is appropriate on a priori grounds.

6 Summing up the Empirical Strategy

The data we use are so myriad that we relegate source information and some details of variable construction to the data appendix. In this section, we summarize the key remaining points about our empirical strategy and data.

Our panel data are at the state-by-year level. The first year for which we can measure the human capital stock well is 1967 and the last year is 2009. Prior to 1967, we have insufficiently good data on the education investments made in the cohorts who are in the labor force. We do not include the District of Columbia as a "state" because it is too integrated with Maryland and Virginia to be considered a small open economy. We only have human capital stock data for Hawaii and Alaska for 1979 onwards. The panel thus has 2126 observations.

6.1 Control Variables

We control for a set of variables, X_{jc}, that are selected to make all else equal. Because our instrumental variables need only be valid conditional on X_{jc}, we take care to include covariates in X_{jc} that increase the credibility of the instrumental variables assumptions (especially the exclusion restriction).

We control for contemporary politics so that the instruments reflect only the committee assignment process, not the general partisan atmosphere. Our specific control variables are: the percentages of the popular vote for U.S. president that belong to each party; the percentage of the votes for the U.S. House of Representatives that belong to each party; and the percentages of seats in state's upper and lower houses that belong to each party. The controls for partisan politics are recorded with timing identical to that of the instruments--namely a two year lag.

Similarly, we control for the industrial composition and socio-economics of state senate chairmen's constituencies so that the instruments for 2-year and 4-year college spending reflect only the direct beneficiaries of the chairman's potential largesse: colleges in his constituency. We do not want the instruments to pick up contemporary forces that politically favor the well-educated, the less-educated, blue-collar workers, and so on.

We control for a full set of state indicator variables and year indicator variables. We also allow for Census division-specific linear time trends. This is because we want the identification to rest on the restriction is that there are no unobserved determinants of growth that are correlated within-state, within-year, within-typical-time-trend-for-the-division with both the political appointment process and education spending. We believe that this restriction is very plausible because we have not heard of a story for such an unobserved variable. To the extent that we heard a story in the past, we have already controlled for it in the variables described above.[18]

6.2 Summary of the Estimating Equations

Summarizing, the second stage estimating equation is:

$$g_{jt}=\kappa_0+\kappa_1 S_{jt}+\kappa_2 U_{jt}+\kappa_3 S_{jt}\cdot\alpha_{jt}+\kappa_4 U_{jt}\cdot a_{jt}+$$
$$\kappa_5 a_{jt}+\boldsymbol{X_{jt}\kappa_6}+\boldsymbol{I_j}\kappa_7+\boldsymbol{I_t\kappa_8}+\boldsymbol{I_d}\cdot t\ \boldsymbol{\kappa_9}+\varepsilon_{jt}$$

where X_{jt} is the set of control variables, κ_7 is the set of state fixed effects, κ_8 is the set of year fixed effects, and κ_9 is a set of Census division-specific linear time trends. We use division-specific linear time trends rather than state-specific linear time trends because 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.

Each human capital stock variable in the above equation is an aggregate based on current investment and previous years' investments, depreciated according to the schedule described above. For instance:

$$S_{jt}=s_{jt}+\sum_{\tau=1}^{9}(1-(\delta_1*\tau))s_{j,t-\tau}+\sum_{k=10}^{34}(1-(\delta_2*\tau))s_{j,t-\tau}$$

where s_{jt} is the investment in high-brow education that enters the labor market in year t, δ_1 is the depreciation rate applied through the first decade, and δ_2 is the depreciation rate applied through the second decade.

For each year's investment in education that enters the labor market, there is a first-stage equation with the political instruments. For instance:

[18] We use division-specific linear time trends rather than state-specific linear time trends because the latter eliminate not only suspect variation but also much of the useful variation in states' educational policies and growth.

$$s_{jt} = \varsigma_1 + \boldsymbol{Z}_{jt}\varsigma_2 + \boldsymbol{X}_{jt}\varsigma_3 + \boldsymbol{I}_j\varsigma_4 + \boldsymbol{I}_t\varsigma_5 + \boldsymbol{I}_d \cdot t\ \varsigma_6 + \upsilon_{jt}$$

where Z_{jt} is the set of political instruments and the remainder of the equation is parallel to the second-stage equation.

Because of the multi-level estimation strategy, we bootstrap the standard errors using the residual method for multi-level models described by Meijer et al (1998).

7 Politics, Proximity to the Frontier, and Growth: Two Illustrative Case Studies

In this section, we narrate two 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 politicians actually boost spending on their state's institutions. We illustrate the relevance of committee membership to the allocation of federal funding, and we illustrate the consequences of funding.

We chose one case that concerns a far-from-the-frontier state, Alabama, and another case that concerns a close-to-the-frontier state, Massachusetts. In each case, a legislator's membership on the 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 Alabama, nor do we observe a prior increase in Alabama's 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 legislator using his position on the Appropriations Committee to generate substantial investments in research universities.

7.1 Alabama

Lister Hill (Democrat) represented Alabama in the Senate from 1938 until 1969. In his final term (1963-69), Hill became a member of the Appropriations committee and delivered payback to his state in the form of a large federal grant that paid for the Alabama Regional Medical Program, the Lister Hill Library building, and new facilities for the Schools of Nursing and Medicine at the University of Alabama.

The money from Hill's grant was disbursed in a single federal budget cycle. Figure 2 depicts the evolution of federal spending for university research in thousands of dollars per capita in Alabama and two comparison states, Mississippi and Georgia, in the 1950s and 1960s.[19] The three states are geographically close. Prior to the Hill grants, Alabama and Mississippi had very similar patterns of education attainment. Also, prior to the Hill grants, Alabama and Georgia had very similar proximity to the technological frontier.

Figure 2 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 to its trend by 1969, when Lister Hill retired from the Senate.

FIGURE 2 HERE

Figure 3 shows the share of age cohorts born in Alabama and Mississippi with medical degrees.[20] We focus on medical degrees because Hill mainly endowed medical research. The calendar year in the horizontal axis refer to the year that each cohort turned 18.[21] 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. Medical degrees in Alabama overtake medical degrees in Mississippi in the years immediately following the Hill grant.

FIGURES 3, 4, and 5 HERE

We turn next to the effect of this federal funding on Alabama's economy. In Figure 4, we show that Alabama's proximity to the frontier was similar to Georgia's before the Hill grant.[22] Instead of Alabama's proximity rising relative

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[19]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.

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

[21]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.

[22]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.

to Georgia's after the 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 5, we examine real economic growth per person 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 neighboring states after 1972. In fact, its growth looks very similar to theirs.

7.3 Massachusetts

Silvio Conte (Republican) represented Massachusetts in the House of Representatives from 1959 until his death in 1991. He became a member of the Appropriations Committee in 1978. While Conte was a self-styled anti-pork crusader, even going so far as to don a pig mask to denounce a proposed infrastructure project in North Dakota, he delivered substantial and sustained payback to Massachusetts in the form of federal funding for research education, especially biomedical and bioengineering education. There are centers named for him at Boston University, Boston College, and the University of Massachusetts. Conte also helped to deliver substantial funding to Harvard and MIT.[23]

We compare Massachusetts and California because they are the states that were closest to the frontier before Conte's grants. Figure 6 shows that federal research funding was higher in Massachusetts than in California in the 1970s, but prior to 1978 the trend was flat in both states. After the appointment of Conte to the Appropriations Committee in 1978, funding climbed steadily in Massachusetts relative to California.

FIGURE 6 HERE

We next turn to a comparison between Massachusetts and California in terms of medical degrees. We focus on medical degrees because so much of Conte's payback was in the form of grants for health sciences. Figure 7 shows that, after Conte's grants, medical degrees in Massachusetts clearly increase relative to those in California.

FIGURE 7 HERE

Interestingly, unlike the Alabama case study, the Conte-induced shock to research funding in Massachusetts appears to have translated into productivity gains for Massachusetts.

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[23]In addition to the centers named for Conte in Massachusetts, there is a research center named for him at the National Institutes of Health. Details of Conte's career were gathered from the website for his congressional papers at the University of Massachusetts. The link is: <http://www.library.umass.edu/spcoll/manuscripts/conte_papers/silvio.html>.

Figure 8 shows that while Massachusetts was substantially further from the frontier than California prior to the Conte shock, 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 largely caught up to California in 15 years. Figure 9 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 industries in the Boston metropolitan area. We hesitate to attribute all of Massachusetts' growth to research 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 a post-grant increase in growth in Alabama.

FIGURES 8 AND 9 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.

8 Results

8.1 Results from the First Stage Regressions

Tables 1 and 2 present estimates from the first-stage equations that are implied by our instrumental variables estimates. That is, they demonstrate how our political committee variables affect education spending, controlling for numerous covariates.

The two left-hand columns of Table 1 are not first-stage regressions but merely regressions that we show because they are interesting. They demonstrate that a senator's probability of appointment to the Appropriations Committee is highly predictive of his state's gaining (another) seat on the Committee. Recall that this probability is the maximum probability among a state's two senators and is computed from political career variables as explained above. The F-statistic on the excluded instrument is 564--which is not altogether surprising because we have deduced the Senate's procedure and there can be few surprises in a Senate of only 100 members. The next column shows that mean probability of appointment to the Committee, among a state's Congressmen, also strongly predicts appointment. The F-statistic on the excluded instrument is 18. We expect the House instruments to have lower predictive power simply because, with so many more legislators from whom to chose and a more fluid legislative body, we cannot predict as accurately who will next be appointed to the committee.

The right-hand column of Table 1 shows the first-stage regression. A one unit increase in the probability, among a state's Senators, of appointment to the Appropriations Committee raises research university expenditure in the state by $691 per person in the affected cohorts.[24] A one unit increase in the mean probability, among a state's House members, of appointment to the Appropriations Committee raises research university spending by $347 per person in the affected cohorts. Because many people in a cohort do not actually attend graduate school at a research university, these numbers represent large increases in spending for the students who actually experience them. The F-statistic on the excluded instruments is 11.

The left-hand column of Table 2 shows that when a state Appropriations or Education committee chairman is appointed who has more four-year college enrollment in his constituency, spending on such colleges rises. Specifically, for every thousand students enrolled in *public* four-year colleges in the constituency of the Education chairman, spending in four-year colleges rises by $79. For every thousand such students enrolled in the constituency of the Appropriations chairman, spending in four-year colleges rises by $28. For every thousand students enrolled in *private* four-year colleges in the Appropriation chairman's constituency, spending in four-year colleges rises by $16. Private four-year enrollment in the Education chairman's constituency does not have an effect that is statistically significantly different from 0. We are not surprised to find that public college enrollment has more of an effect than private college enrollment. As noted above, there are more direct channels by which politicians can funnel spending to public colleges than to private ones.

The right-hand column of Table 2 shows a similar regression for two-year colleges. For every thousand students enrolled in public and private two-year colleges in the constituency of the Education chairman, spending in two-year colleges rises by--respectively--$19 and $43. Enrollment in the Appropriations chairman's constituency has statistically insignificant effects. At first it may seem surprising that the per-student effect of private two-year colleges is bigger than the per-student of public ones. However, this is probably a reflection of the fact that private two-year colleges often have small, mostly full-time enrollment while public four-year colleges often have fairly massive, part-time enrollment.

The regressions for both four-year and two-year college spending have F-statistics on the excluded instruments that are greater than 40. In summary, our first stage estimates suggest that political committee appointments generate significant variation in states' investments in education, and we have identified instruments for each type of higher education.

8.2 The Effects of Education on Growth

Table 3 shows estimated coefficients from our main equation that estimates the effect of education on growth. The human capital stocks are differentiated by

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[24] Because graduate education typically begins last four years (age 22 to 25), these are dollars per person who is aged 22 to 25 in the state.

type and interacted with proximity to the technological frontier. (Since we hold proximity constant at its initial level, we do not show a control for its main effect, which would be absorbed by state fixed effects.) For ease of interpretation, we show the effects of human capital for states that are at the technological frontier and states at the technological frontier. The effects for states far from the technological frontier can be read from the first three coefficients in each column.

In the left-hand column, we associate economic growth with the state where it occurs so that the effects of migration are felt. In the right-hand column, we un-do the effects of migration on growth by apportioning growth to states based on where people were born.[25]

Let us focus first on states at the technological frontier and then work our way up Table 3. For a state at the technological frontier, a thousand dollars of research-type human capital per person raises growth in per capita income by 0.07 percentage points. For a state at the frontier, a thousand dollars of four-year college type human capital per person raises growth in per capita income by 0.03 percentage points. Finally, for a state at the frontier, two-year college type human capital has a statistically insignificant effect on the growth in per capita income.

For a state far from the technological frontier, the effects of education on growth are quite different. A thousand dollars of research-type human capital per person increases growth in per capita income by an amount that is not statistically significantly different from 0 (the point estimate is only 0.01 percentage points). A thousand dollars of four-year college type human capital raises growth in per capita income by 0.04 percentage points. Finally, two-year college type human capital has an effect on growth that is not statistically significantly different from 0 (the point estimate is 0.02).

A state midway to the frontier experienced growth effects in between those experienced by the at-the-frontier and far-from-frontier state. The effects shown for the midway state are very close to what we see if we had not interacted the education variables with the proximity variables.

So far, we have described the estimated effects on the growth in per capita income. However, the estimated effects on the growth in per capita GSP are extremely similar.

The bottom line is that, at least with migration, states that are close to and far from the frontier experience different growth effects from research-type human capital. However, four-year college-type human capital generates

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[25]We have also tried apportioning growth based on more complex algorithms for the relationship between where people are born, educated, and reside as adults. We based these on the Internal Revenue Service's migration data files and on Census microdata files. However, these alternative algorithms produced results quite similar to those based more simply on state of birth. Moreover, the Internal Revenue Service-based data is inferior is some ways because, while it is annual population not decennial sample data, it does not allow us to take explicit account of each person's cohort.

similar growth in all U.S. states. Of course, we cannot extrapolate this finding to countries that much further from the technological frontier than the U.S. states like Mississippi or Arkansas were in 1967. What is far from the frontier in the U.S. may be relatively close to the frontier elsewhere. Two-year college type human capital does not seem to affect growth in U.S. states. Of course, our results do not imply that two-year college type human capital is unproductive. They just imply that it does not change productivity growth relative to dollars invested in other capital.

In some columns of Table 3 we un-do migration by apportioning growth back to states based on residents' states of birth. Un-doing migration strongly affects the coefficients on research-type human capital but leaves the other coefficients largely unchanged. For instance, the effect of research-type human capital on at-the-frontier states falls from 0.07 to 0.04 percentage points, and the effect of research-type human capital on far-from-the-frontier states rises from 0.01 to (a still statistically insignificant) 0.02 percentage points. These results suggest that people with research-type education are elastic in their locational choices and migrate away from their home state if its economy is not a good match for their skills. In other words, it is hard for a far-from-the-frontier state to keep the benefits of research-type investments in the state.

On the whole, the results shown in Table 3 support the notion that some education has a positive, causal effect on growth. The results also suggest that we were right to insist upon distinguishing among different types of human capital and different technological environments. It seems likely that the economies of close-to-the-frontier states depends much more on technological innovation for their growth than do far-from-the-frontier states.

Because four-year college education conveys such a wide range of skills, it is hard to give a strong interpretation to the fact that its effect appears to be similar across U.S. states. That is, the marginal dollar could be invested in undergraduate computer science in one state and undergraduate communications in another. Because it is not random which subject area gets the marginal investments, the marginal investments in computer science and communications could the same effect on growth in the states in which they take place, even if their effects on growth are sensitive to proximity to the frontier. This is something we cannot check because, at least in this paper, we do not have measures of or instruments for human capital by subject area.[26]

In Table 4, we implement numerous specification checks. None of these has an important effect on the results. The checks that we consider most important vary the depreciation schedule that we apply to education investments to construct human capital stocks. Obviously, we cannot be entirely flexible about the depreciation rates, but we consider two other schedules that are supported by research on cognition. In other specification checks, we drop some of our political control variables, drop the control for

[26] These are issues we are currently studying.

federal highway-type spending, or drop the industrial and socio-economic characteristics of state senate chairmen's constituencies. Finally, we use labor productivity (at the beginning of the period) as our measure of proximity to the frontier, as opposed a measure of proximity based on patents.

8.3 Effects on Patenting, a Direct Measure of Innovation

Having suggested that innovation is the most likely channel for externalities and growth effects from research-type spending, we examine patenting in Table 5. We also study patenting in other work (Aghion, Dewatripont, Hoxby, Mas-Colell, and Sapir, 2010).

The regression shown in Table 5 has the same set up as those in Table 3 except that the dependent variable is patents per thousand people aged 25 to 50. This variable has a mean of 0.62 and a residual standard deviation of 0.31 (residual from state effects, year effects, and Census division time trends).

To avoid having a variable based on patents (even one from 1963, which predates the years we study) on both sides of the equation, we use the measure of proximity based on a state's rank in labor productivity in 1960. It is is standardized so that the farthest-from-the-frontier state has proximity of 0 and the at-the-frontier state has proximity of 1.

In Table 5, we show that, for a state at the technological frontier, a thousand dollars per person of research education-type human capital raises patents per thousand people by 0.04. A thousand dollars per person of four-year college-type human capital raises patents per thousand people by 0.02. Increases in two-year college-type human capital have no discernable effect on patenting.

A state midway to the frontier has 0.02 and 0.01 patents per thousand people for each thousand dollars of, respectively, research-type and four-year college-type human capital. In a state far from the technological frontier, however, an exogenous increase in any type of human capital has no effect on patenting that is statistically significant.

In short, patenting--a fairly direct measures of technological innovation--suggests at least one mechanism by which high brow education affects productivity growth. This inventive effect is statistically distinguishable only in U.S. states that are at least midway to the technological frontier.

9 Discussion

We find support for the hypothesis that some investments in education raise growth. For the U.S., where all states are fairly close to the world's technological frontier, we find positive growth effects of exogenous shocks to investments in four-year college education, for all states. We do not find that exogenous shocks to investment in two-year college education increase growth. We find that exogenous shocks to research-type education have larger positive growth effects in states that are closer to the technological frontier. In part, this is because research-type investment shocks induce the beneficiaries of such education to migrate to close-to-the frontier states from far-from-the-frontier states. Put another way, Massachusetts, California, or New Jersey may benefit as much from an investment in Mississippi's research universities as Mississippi does. Finally, we use patents to show that technological innovation is a plausible channel the growth effects of both research and four-year college type education.

The contributions of this paper are several. We make a serious attempt to estimate effects of education on growth that are plausibly causal. We measure actual investments in education, not mean educational attainment, which is both crude and an endogenous choice. We measure the investments in different *types* of education. Using depreciation rates based on cognition research, we construct human capital stocks. We attempt to embed our estimation in a coherent model of the relationship between education and growth. Overall, we have tried to change the conversation from one about correlations between average education and growth to one about specific mechanisms by which exogenous education investments affect economic growth and technological innovation.

We recognize some areas in which more work is warranted. First, it would be very useful to identify the causal effect of primary and secondary education on growth. Finding valid instruments is the challenge. Second, identifying the causal effect of education in different subject areas is important. Third, further study of the effects of education on migration would be interesting. Finally, it would be useful to have a better understanding of the intermediating mechanisms by which education affects growth--perhaps via the study of particular industries.

10 References

Acemoglu, Daron (1997). "Training and Innovation in an Imperfect Labor Market", Review of Economic Studies, 64(3), 445-64

Acemoglu, Daron, Aghion, Philippe and Fabrizio Zilibotti (2002). "Distance to Frontier, Selection, and Economic Growth", Journal of the European Economic Association, 4(1), 37-74.

Acemoglu, D. (2009). Introduction to Modern Economic Growth. Princeton, NJ: Princeton University Press.

Adams, J.D. (2002). "Comparative Localization of Academic and Industrial Spillovers," Journal of Economic Geography, 2(3): 253-278.

Aghion, P., L. Boustan, C. Hoxby, and J. Vandenbussche (2005). "Exploiting States' Mistakes to Identify the Causal Impact of Higher Education on Growth." NBER conference paper, http://www.nber.org/confer/2005/si2005/ed/hoxby.pdf. Revised version forthcoming in Brookings Papers on Economic Activity.

Aghion, P, M. Dewatripont, C. Hoxby, A. Mas-Colell, and A. Sapir (2010). "The Governance and Performance of Research Universities: Evidence from Europe and the U.S." Economic Policy.

Andersson, Roland, John M. Quigley, and Mats Wilhelmsson (2004). "University Decentralization as Regional Policy: The Swedish Experiment." Journal of Economic Geography, 4(4), 371-388.
Anselin, L., Varga, A. and Acs, Z. (1997). "Local Geographic Spillovers between University Research and High Technology Innovations," Journal of Urban Economics, 42.
Bahrick, Harry P. and Lynda K. Hall (1991). "Lifetime Maintenance of High School Mathematics Content," Journal of Experimental Psychology: General, Vol. 120, No. 1, pp. 20-33.
Barro, Robert J., and Xavier Sala-i-Martin (1991). "Convergence across States and Regions," Brookings Papers on Economic Activity, 22, 107-182.
Benhabib, Jess and Mark Spiegel (1994). "The Role of Human Capital in Economic Development: Evidence from Aggregate Cross-Country Data." Journal of Monetary Economics, 34, 143-174
Bils, Mark and Peter Klenow (2000), "Does Schooling Cause Growth?", American Economic Review, 90, 1160-1183
Bound, John, J Groen, G Kezdi, and Sarah E. Turner (2004). "Trade in University Training: Cross-State Variation in the Production and Stock of College-Educated Labor." Journal of Econometrics, 121(1-2), 143-173.
Bullock, C., and J. Sprague (1969). "A Research Note on the Committee Reassignments of Southern Democratic Congressmen," The Journal of Politics, Vol. 31, No. 2, pp. 493-512.
Camdessus, Michel (2004), Vers une Nouvelle Croissance pour la France, La Documentation Francaise.
Carnegie Foundation for the Advancement of Teaching (2005). Carnegie Classification of Institutions of Higher Education." Electronic file. http://www.carnegiefoundation.org/classifications/
Conway, Martin, Gillian Cohen, and Nicola Stanhope (1992). "Very Long-term Memory for Knowledge Acquired at School and University," Applied Cognitive Psychology, Vol. 6, No. 6, pp. 467–82.
Custers, Eugène J.F.M. (2010). "Long-term retention of basic science knowledge: a review study," Advances in Health Sciences Education, Vol 15, No. 1, 109-28.
Feller, I. (2002). "The Distribution of Federal Academic R&D Awards: Policy Agendas and Structural Determinants," Journal of Policy Analysis and Management.
Fischer, M.M. and A. Varga (2003). "Spatial Knowledge Spillovers and University Research: Evidence from Austria," Annals of Regional Science, Vol. 37, 303-322.
Florax, R. (1992). The University: A Regional Booster? Aldershot: Avebury.
Francis, W.L. (1995) "Leadership, Party Caucuses, and Committees in U. S. State Legislatures," Legislative Studies Quarterly, Vol. 10, No. 2, pp. 243-257.
Frisch, S.A. and S.Q Kelly (2006). House Committee Request Data, 80th-103rd Congress. Electronic files. [obtained directly from authors, rather than

ICPSR].

Frisch, S.A. and S.Q Kelly (2004). "Self-Selection Reconsidered: House Committee Assignment Requests and Constituency Characteristics," Political Research Quarterly, 57(2), 325-336.

Gawthrop, L.C. (1966) "Changing Membership Patterns in House Committees," The American Political Science Review, Vol. 60, No. 2, pp. 366-373.

Gertzog, I.N. "The Routinization of Committee Assignments in the U. S. House of Representatives," American Journal of Political Science, Vol. 20, No. 4, pp. 693-712.

Goolsbee, A. (1998). "Does Government R&D Policy Mainly Benefit Scientists and Engineers?" American Economic Review, 22, 298-302

Greenberg, D.S. (2001). Science, Money and Politics. Chicago, IL: The University of Chicago Press.

Hall, B. H. (2006). "2002 Updates to NBER Patent Data." Electronic file. http://elsa.berkeley.edu/~bhhall/bhdata.html.

Hall, B. H., A. B. Jaffe, and M. Tratjenberg (2001). "The NBER Patent Citation Data File: Lessons, Insights and Methodological Tools." NBER Working Paper 8498.

Hedlund, R.D. "Entering the Committee System: State Committee Assignments," The Western Political Quarterly, Vol. 42, No. 4, pp. 597-625.

Hedlund, R.D. and S.C. Patterson (1992). "The Electoral Antecedents of State Legislative Committee Assignments," Legislative Studies Quarterly, Vol. 17, No. 4, pp. 539-559.

Hoxby, C.M. (2008). "School Spending, Income, and Inequality: The Efficient Redistribution Hypothesis." Stanford University manuscript.

Inter-university Consortium for Political and Social Research and Congressional Quarterly, Inc. United States Congressional Roll Call Voting Records, 1789-1996. Electronic file, ICPSR00004 version 2. Ann Arbor, MI: Inter-university Consortium for Political and Social Research. Also, Washington, DC: Congressional Quarterly, Inc. [producers], 1997. Ann Arbor, MI: Inter-university Consortium for Political and Social Research [distributor], 1997.

Inter-university Consortium for Political and Social Research and C. McKibbin. Roster of United States Congressional Officeholders and Biographical Characteristics of Members of the United States Congress, 1789-1996: Merged Data. Electronic file, 10th ICPSR edition. Ann Arbor, MI: Inter-university Consortium for Political and Social Research [producer and distributor], 1997.

Jaffe, A. (1989). "Real Effects of Academic Research," American Economic Review, 79:957-970.

Krueger, Alan and Mikael Lindahl (2001). "Education for Growth: Why and for Whom?" Journal of Economic Literature, 39, 1101-1136.

Lucas, Robert (1988). "On the Mechanics of Economic Development", Journal of Monetary Economics, 22, 3-42.

Mankiw, Gregory, Romer, David, and David Weil (1992), "A Contribution to the

Empirics of Economic Growth." Quarterly Journal of Economics, 107, 407-438.

Masters, N.A. (1961). "Committee Assignments in the House of Representatives," The American Political Science Review, Vol. 55, No. 2, pp. 345-357.

Meijer, E., F.M.T.A. Busing, and R. Van der Leeden (1998). "Estimating bootstrap confidence intervals for two-level models," in J. J. Hox and E. D. De Leeuw (eds.), Assumptions, robustness, and estimation methods in multivariate modeling. Amsterdam: TT Publicaties, pp. 35-47..

Munger, M.C. (1988). "Allocation of Desirable Committee Assignments: Extended Queues versus Committee Expansion," American Journal of Political Science, Vol. 32, No. 2, pp. 317-344.

National Center for Education Statistics, Institute for Education Sciences, U.S. Department of Education. Integrated Postsecondary Education Data System. Enrollment, Finance, Residence and Migration, and Institutional Characteristics files. 1980 and 1984 through 2008 editions. Electronic data. Washington, DC: U.S. Department of Education, retrieved August 2008 (except for 2008 data, which were retrieved January 2009).

Nelson, Richard, and Edmund Phelps (1966). "Investment in Humans, Technological Diffusion and Economic Growth." American Economic Review, 56, 69-75.

Payne, A. (2003), "The Effects of Congressional Appropriation Committee Membership on the Distribution of Federal Research Funding to Universities," Economic Inquiry, Vol. 41, No. 2, 325-345.

Roberts, B.E. (1990) "A Dead Senator Tells No Lies: Seniority and the Distribution of Federal Benefits," American Journal of Political Science, Vol. 34, No. 1, pp. 31-58.

Rohde, D.W. and K.A. Shepsle (1973). "Democratic Committee Assignments in the House of Representatives: Strategic Aspects of a Social Choice Process," The American Political Science Review, Vol. 67, No. 3, pp. 889-905.

Romer, Paul (2000). "Should the Government Subsidize Supply or Demand in the Market for Scientists and Engineers?" NBER Working Paper No 7723.

Rosenthal, H.L., and K.T. Poole. United States Congressional Roll Call Voting Records, 1789-1990. Electronic file, reformatted data, 2nd ICPSR release. Pittsburgh, Carnegie Mellon University, Graduate School of Industrial Administration [producers], 1991. Ann Arbor, MI: Inter-university Consortium for Political and Social Research [distributor], 2000.

Sapir, A. (ed.), Philippe Aghion (author), Giuseppe Bertola (author), Martin Hellwig (author), Jean Pisani-Ferry (author), Dariusz Rosati (author), and Jose Vinals (author) (2004). An Agenda for a Growing Europe. Oxford: Oxford University Press.

Scherer, F and K. Hue (1992). "Top Managers' Education and R&D Investment", Research Policy, 21, 507-511.

Sinclair, B. (1988). "The Distribution of Committee Positions in the U.S. Senate: Explaining Institutional Change," American Journal of Political

Science, Vol. 32, No. 2, pp. 276-301.
Stewart, C. and T. Groseclose (1999). "The Value of Committee Seats in the United States Senate, 1947-91," American Journal of Political Science, Vol. 43, No. 3, pp. 963-973.
Stewart, C. and J. Woon (2007). Congressional Committee Assignments Data 1993-2007. Electronic files.
Swift, E.K., R.G. Brookshire, D.T. Canon, E.C. Fink, J.R. Hibbing, B.D. Humes, M.J. Malbin, and K.C. Martis (2004). Database of [United States] Congressional Historical Statistics, 1789-1989. Electronic file, ICPSR version. Ann Arbor, MI: Inter-university Consortium for Political and Social Research [producer], 2000. Ann Arbor, MI: Inter-university Consortium for Political and Social Research [distributor].
U.S. Dept. of Commerce, Bureau of the Census (2007). Census Tract-level Data, 1960. Electronic data, ICPSR version. Washington, DC: U.S. Dept. of Commerce, Bureau of the Census [producer, 1971]. Ann Arbor, MI: Inter-university Consortium for Political and Social Research [distributor, 2007].
U.S. Department of Commerce, Bureau of Economic Analysis (2008). Regional Economic Information System, State Annual Summary Tables for Per Capital Personal Income, 1969-2008. Electronic data. Washington, DC: Bureau of Economic Analysis.
U.S. Department of Education. Higher Education General Information System. Enrollment, Finance Statistics, Student Charges, Residence and Migration, and Institutional Characteristics files. 1966 through 1986 editions. Electronic data. Washington, DC: U.S. Department of Education, 1966 to 1986 (retrieved on various dates).
Vandenbussche, Jerome, Aghion, Philippe, and Costas Meghir (2004). "Growth and the Composition of Human Capital." Journal of Economic Growth, 11(2), 97-127.
Varga, A (1998). University Research and Regional Innovation. Boston: Kluwer Academic Publishers

10 Data Appendix

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

10.1 Measures of Per Capita Personal Income and GSP

We use U.S. Department of Commerce (2008) for state-by-year level measures of per capita personal income and GSP. We construct annual growth from the published data.

10.2 Measures of Patenting

We use inventive ("utility") patents by year and state from Hall, Jaffe, and

Tratjenberg (2001) and Hall (2006). Each patents is associated with the state of residence of the person who registers the patent. These data are available from the National Bureau of Economic Research (www.nber.org).

Patents, along with the population-by-age data (see below), are used to construct our measure of proximity to the frontier. Our main measure of proximity to the frontier is a state's number of inventive patents relative to the size of its economy in 1963. We standardize this measure by subtracting the typical minimum of the measure among states and then dividing by the maximum among states. Thus, our measure of proximity varies between zero and one.

10.3 Measures of Educational Investment Based on Spending

10.3.1 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.

10..3.2 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, 2008). Note that CASPAR is a longitudinal compilation of data taken from two data sources based on administrative data--that is, postsecondary institutions annual self-reports to the government. These two sources are 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 missing observations. Carnegie classification codes are based on the old (HEGIS-era) classification system published by the Carnegie Foundation for the Advancement of Teaching (2005). Most institutions' Carnegie codes are recorded in CASPAR as an institutional characteristic, but --if they are not--we use data directly from the Carnegie Foundation.

For the most recent school years, spending data are not yet available in the

CASPAR data. Thus, for the school years from 1993-94 onwards, we use data from the financial and institutional characteristics files of the Integrated Postsecondary Education Data System (National Center for Education Statistics, 1980 and 1984 to 2008). 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.

10.3.3 Spending on Research Type Education

For spending on research type education, we record the total expenditures of postsecondary institutions that fit into one of the following categories: institutions with a "Research 1", "Research 2", "Doctoral 1" or "Doctoral 2" Carnegie classification. We also include institutions that grant the doctoral degree and that have a "Medical" or "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.

10.3.4 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 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 four-year type education are from the same sources as the data on spending on two-year type education.

10.4 Instrumental Variables Based on Political Committees

Our understanding of the connection between political appointments and funding, especially education funding, owes much to Roberts (1990), Greenberg (2001), Feller (2002), and Payne (2003).

Our understanding of the process of committee assignments owes much to Masters (1961), Bullock and Sprague (1969), Gawthrop (1966), Rohde and Shepsle (1973), Gertzog (1976), Munger (1988), Sinclair (1988), Hedlund (1989), Hedlund and Patterson (1992), Francis (1995), Stewart and Groseclose (1999), and Frisch and Kelly (2004). However, we reprocessed all of the raw data for ourselves (see below) and reformulated the empirical procedure through which legislators are appointed to committees. The aforementioned literature provides ideas about the procedure, but we found that some of the ideas were empirically invalid and other ideas were valid but had weak explanatory power. The process we describe below is the one with by far the most explanatory power, and it is therefore the most likely to be correct, as an empirical matter.

10.4.1 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.

In order to accumulate complete political histories for every member of Congress, we matched the above data to all available Congressional Roster data, Congressional committee membership data, and Congressional Committee Request data--namely: Inter-university Consortium for Political and Social Research and McKibbon (1997), Inter-university Consortium for Political and Social Research and Congressional Quarterly (1997), Rosenthal and Poole (2000), Swift et al (2004), Stewart and Woon (2007), Frisch and Kelly (2006).

We corrected numerous minor errors in individual legislator's career histories. Many of the errors are due to miscoding of a legislator's identification number or to mix-ups between a legislator and a relative who succeeds him in office, often by means of a gubernatorial appointment or special election.

With the full and corrected array of data on Congressional and committee membership at each point in time, we found the moment at which each Appropriations Committee vacancy arose and constructed, for each of these moments, the membership of the Appropriations committee by party, state, and seniority and the composition of each house of Congress by party, state, and seniority. We also constructed the membership of every other exclusive committee so as to know which legislators were not eligible to fill the Appropriations Committee vacancy. The exclusive committees in the House of Representatives are Appropriations, Ways and Means, and Rules. The exclusive committees in the Senate are Finance, Armed Services, and Foreign Relations. These represent only a small fraction of the total number of committees.

We compute the probability that each congressmen is appointed to the Appropriations Committee on each possible date. We do this using a regression with numerous interaction terms, but the computation can be described in words. The likelihood is zero is there is no within-party vacancy or if the congressmen is an incumbent member of the Committee. It is close to zero if the congressmen is a high ranking member of another exclusive committee. After ruling these congressmen out, the remaining legislators are ordered according to the within-party representation gap that their state has at the moment the vacancy arises. Within their state and between states with the same representation gap, legislators are ordered by seniority. The legislator who is first in line has the highest probability of being appointed, and so on.

We aggregate the probabilities by state at each point in time: the maximum probability of appointment enjoyed by any of the state's legislators in the house in question, the mean probability of appointment enjoyed by the state's legislators in the house in question, and the sum of the probabilities of appointment enjoyed by the state's legislators in the house in question.

10.4.2 Chairmen of State Education and State Appropriations Committees

For 1975 onward, we collect information on state legislators from a pair of volumes published by the Council on State Governments. The first volume, State Legislative Leadership, Committees and Staff, contains rosters of committee chairpersons. We assemble data on both the House and Senate's Education and Appropriations committees in each state. If a chamber does not have a committee called "Appropriations," we gather data on the committee that fulfills the same function in the state. (The most frequent alternative name is "Finance," but there are also states with more idiosyncratic committee names). A companion volume, Selected State Officials and the Legislatures, provides information on street addresses and district numbers for each state representative against which we match our roster of committee chairpersons.

For the years prior to 1975, membership on state legislative committees is published in each state's political directory or legislative manual. These vary widely in their organization and detail. Data from all states with political directories that were archived in the University of California, Harvard, or Stanford library system were used in person. Legislative information for states whose directories were not so archived or states whose directories did not include standing committee assignments in some years was gathered with the assistance of librarians in state law libraries. Any information missing at this point was requested by e-mail from the relevant state's Senate historian. In no case did the historian fail to respond with all information at his disposal. Thus, the few remaining missing observations are due to missing information in the office of the state Senate itself. A complete list of state-specific sources is provided below in the table.

For the years prior to 1975, we continue to use the volume Selected State Officials and the Legislatures, which is published back to 1950 as an appendix to the Book of the States, to match representatives to their street addresses and district numbers.

Ideally, we would link state committee chairmen to the exact boundaries of their constituencies. However, before 1990, Census data was not matched to state senatorial districts. Furthermore, because the boundaries of the districts change over time, we cannot retroject the 1990 boundaries back in time using digital mapping tools without obtaining incorrect boundaries.

In most states, state senate constituencies are more closely aligned with counties than any other geography. Thus, we first match each state senate chairman to the county of his constituency. To allow for the more idiosyncratic constituency boundaries of other states, we also match each chairman to his post office (in practice, municipalities except in rural areas) and 3-digit zip codes. For legislators who worked before zip codes were invented in 1963, we match their street addresses to zip codes using the Postal Service website (www.usps.com). If we know only a legislator's town of residence, we match him to the zip code for that town using www.city-data.com.

10.4.3 Enrollment in the Institutions of Higher Education in the Constituencies of State Senate Education and Appropriations Chairmen

Using U.S. Department of Education (1966 to 1986, "HEGIS"), we match each state committee chairman with the institutions of higher education that fall into his county, post office (municipality), and 3-digit zip code area. We then create aggregate statistics on the institutions for each of these areas: most importantly enrollment but also some financial and other characteristics that we did not use. These statistics are aggregated separately for four-year private, four-year public, two-year private, and two-year public institutions. The type of college is based on the old (HEGIS-era) system published by the Carnegie Foundation for the Advancement of Teaching (2005). The control of colleges is part of the HEGIS Institutional Characteristics file.

10.5 Industrial and Socioeconomic Characteristics of the Constituencies of State Senate Education and Appropriations Chairmen

Using U.S. Department of Commerce (2007), we link each state senate chairman to the following characteristics of his county in 1960: share black, share Hispanic, mean family income, share of adults with various levels of completed education, and share employed in various industries.

10.6 Political Control Variables

We control for the following partisan politics variables: the percentage of the popular vote for U.S. president that was Democratic, the percentage of the popular vote for U.S. president that was neither Democratic nor Republican, the percentage of the votes for the U.S. House of Representatives that were Democratic, the percentage of the votes for the U.S. House of Representatives that were neither Democratic nor Republican, the percentage of seats in the state's upper house (Senate) occupied by Democrats, and the percentage of seats in the state's lower house occupied by Democrats.

To ensure that we control for contemporary politics that could have affected education spending other than through committee appointments, we create averages for the above political variables for several time intervals. The first interval is the 13 years the cohort would typically have been in primary and secondary school (state political variables); the second interval is the two years they would typically have been in two-year college (state political variables); the third interval is the four years they would typically have been in four-year college (state political variables); and the fourth interval is the four years they would typically have been in graduate school (federal political variables).

10.7 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 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 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 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 upon 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).

10.9 Measures of Federal Expenditures by State

One can track the total federal allocation to states either by gathering data on the geographic distribution of federal appropriations, or by identifying the sources of state revenue. We chose the latter because of the consistency of series on state budgets over time.

From 1978 on, we use the Annual Survey of Governments finance files archived at ICPSR from 1978-1991 and on-line at the Census Bureau from 1992-2000 (http://www.census.gov/govs/www/state.html). Before 1978, we rely on a corresponding paper source, collected annually by the Census Bureau, and called variously the Compendium of State Government Finances (1950-1965) and State Government Finances (1966-1977).

We identify five categories of federal expenditure consistently from 1950-2000: education, highways, public welfare, health and hospitals, and the employment security. We collapse spending for other purposes, including agriculture, natural resource management and housing, into a single remainder category.

Sources for state-level political data

State	Name of directory
AL	Alabama official and statistical register
CA	Handbook of information for use of members of the California Legislature General Session
CA	California Legislature at Sacramento
CT	Connecticut State register and manual
FL	Directory of Florida Government
GA	Georgia's Official Register
GA	Georgia's Official and Statistical Register
IA	Iowa Official Register
IN	Roster of state and local officials of the State of Indiana
KS	Kansas Blue Book
KS	Kansas Directory
LA	Roster of Officials
MA	A manual for the use of the General Court
MD	Maryland Manual
MI	Michigan official directory and legislative manual
MI	Michigan manual
MN	Legislative manual of the state of Minnesota (and alternate titles)
MN	The Minnesota legislative manual
MO	Official manual of the state of Missouri
MS	Mississippi official and statistical register.
NC	North Carolina Manual
NE	Nebraska Blue Book
NH	Manual for the General Court
NJ	Manual of the Legislature of New Jersey
NM	New Mexico Blue Book
ND	North Dakota Blue Book
NV	Legislative manual, State of Nevada
NY	New York red book
OH	Official roster: federal, state, county, and departmental information
OK	Directory and manual of the State of Oklahoma
OR	Oregon Blue Book
PA	Pennsylvania state manual.
RI	Manual for the use of the General Assembly of the state of Rhode Island
SC	Legislative manual - General Assembly of South Carolina
SD	South Dakota Legislative Manual
TN	Tennessee Blue Book
UT	Utah official roster
VA	Manual of the Senate and House of Delegates
VT	Vermont legislative directory and state manual
WA	Joint rules, rules of the Senate and rules of the House of the State Legislature of Washington
WI	Wisconsin Blue Book
WV	West Virginia Blue Book
WY	Wyoming Official Directory

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

11.1 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).

11.2 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.

11.3 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:

$$w_{s,t+1} = \zeta(1-\beta)A_{t+1}U_{f,t+1}^{\beta}S_{f,t+1}^{-\beta} = \delta(U_{f,t+1}^{\beta}S_{f,t+1}^{1-\beta})\lambda(1-\sigma)u_{m,t+1}^{\sigma}s_{m,t+1}^{-\sigma}(\bar{A}_t - A_t) \tag{16}$$

and

$$w_{u,t+1} = \zeta\beta A_{t+1}U_{f,t+1}^{\beta-1}S_{f,t+1}^{1-\beta} = \delta(U_{f,t+1}^{\beta}S_{f,t+1}^{1-\beta})\lambda\sigma u_{m,t+1}^{\sigma-1}s_{m,t+1}^{1-\sigma}(\bar{A}_t - A_t) \tag{17}$$

which imply

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

and

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

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

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

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

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

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

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

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

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

This establishes Lemma 4.

12 Appendix 2: Proof of Proposition 3

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

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

The RHS is linear in U and S and therefore from there it is straightforward to obtain parts (i) and (ii) of the Proposition. To obtain part (iii), we first note that the cross derivative of the right hand side of (24) with respect to a and μ^* is positive. Second, we prove below that at the maximum value of μ^*compatible with an interior solution, the first partial derivative of the right hand side of (24) with respect to a is negative.

Let us call

$$R(a,\mu) \equiv h(a)^{-\phi-\beta}[Uh(a) + \frac{1-\phi}{\phi}S(1-\mu) + \frac{h(a)^\phi}{\phi\lambda\gamma}]$$

We have

$$\frac{\partial R}{\partial a}(a,\mu) = h'(a)h(a)^{-1-\beta}\left[(1-\phi-\beta)Uh(a)^{-\phi+1} - \frac{1-\phi}{\phi}(\phi+\beta)h(a)^{-\phi}S(1-\mu) - \frac{\beta}{\phi\lambda\gamma}\right]$$

Let us now define $\mu_{\max}(a)$ by

$$\frac{(U-U^*)}{(S(1-\mu_{\max}(a)) - S^*)} = \frac{\beta+\Delta(1-\beta)+\alpha^{-3}}{\beta+\Delta(1-\beta)+\Delta\alpha^{-3}}\frac{\Gamma}{h(a)}$$

We have

$$\frac{\partial R}{\partial a}(a,\mu_{\max}(a)) = \frac{h'(a)h(a)^{-1-\beta}}{\beta+\Delta(1-\beta)+\Delta\alpha^{-3}}$$

$$\left\{\Delta h(a)^{-\phi}S(1-\mu_{\max}(a))\left[\frac{\alpha^{-3}\Psi}{\sigma}(\sigma-\phi-\beta) - \left(\frac{1-\phi}{1-\sigma}\right)\right] - \frac{\beta}{\phi\lambda\gamma}[\Delta\phi + (1-\phi) + \Delta\alpha^{-3}]\right\}$$

which is positive since $\sigma - \phi - \beta < 0$. This completes the proof of (iii).

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

$$\frac{\partial\mu^*}{\partial S} = \frac{-(1-\mu^*)}{Mh(a)^{\beta+\phi}a^{-1}\frac{\phi}{1-\phi}\frac{(1+\frac{\delta}{\zeta})\Gamma^{1-\beta}}{\beta\delta\lambda\gamma(1-\phi)} - S}$$

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

Figure 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)

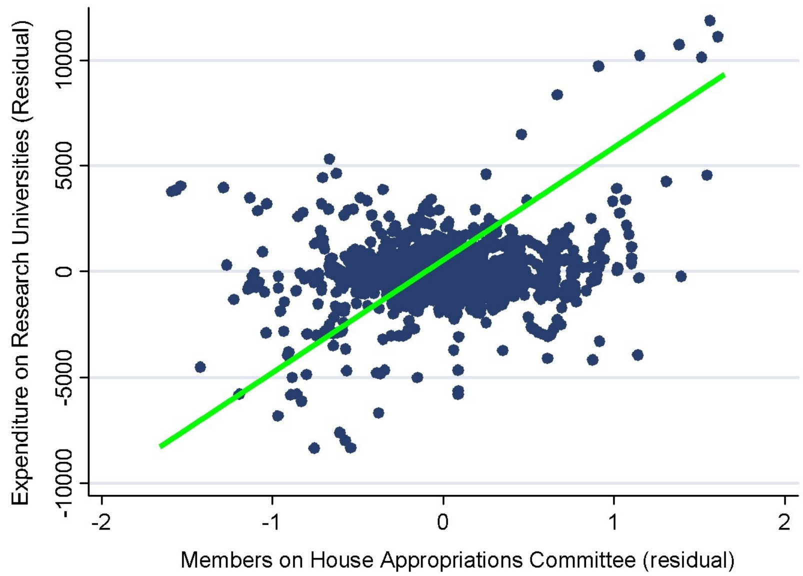

Figure 2

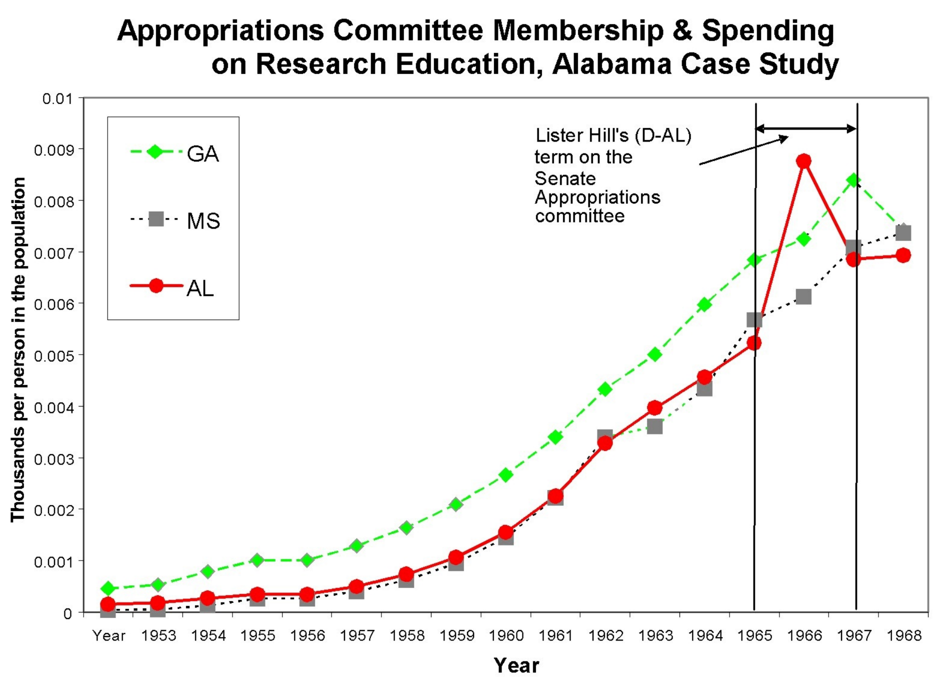

Figure 3

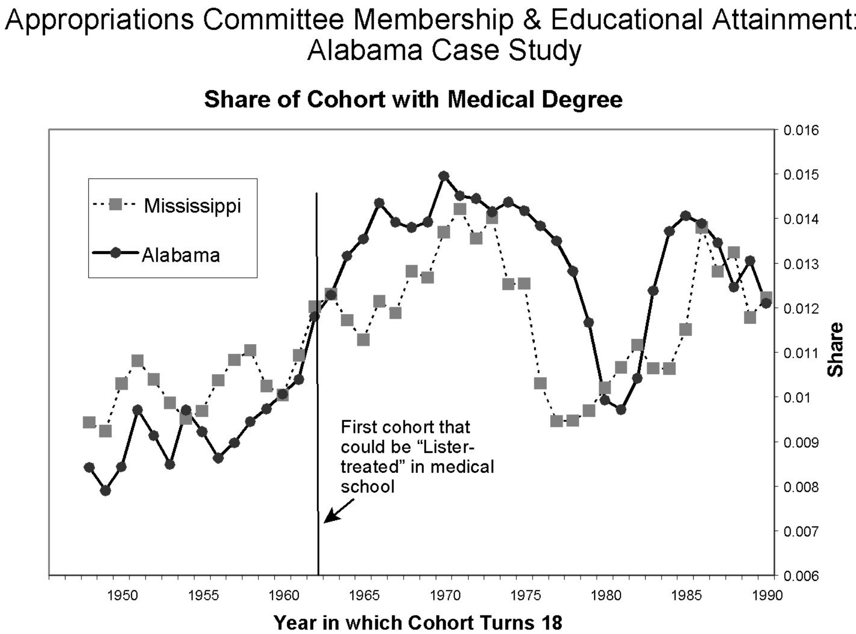

Figure 4

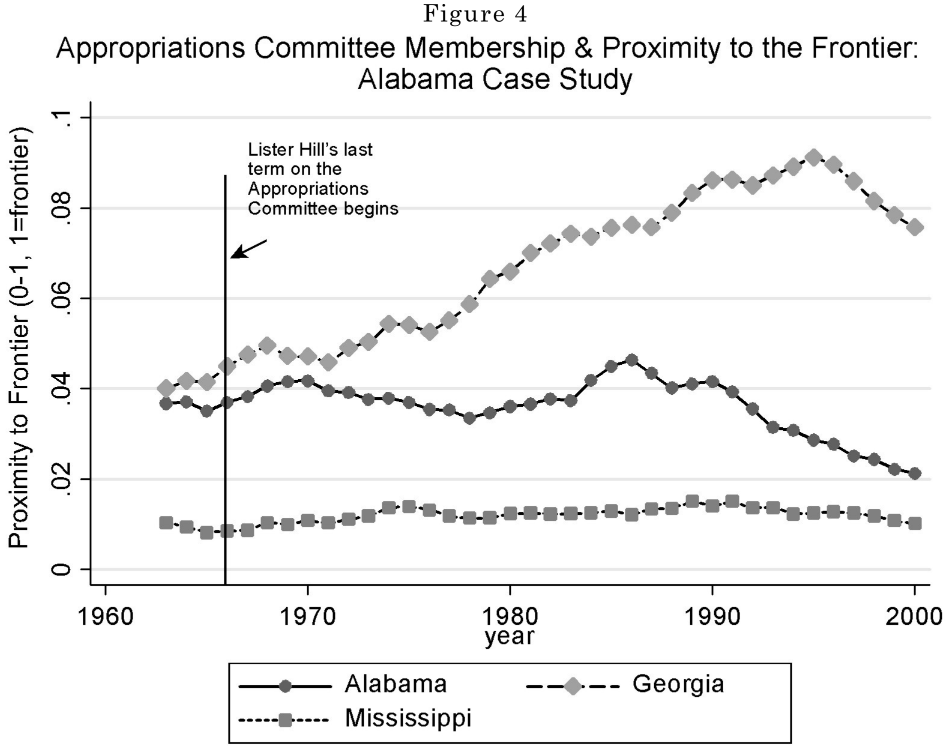

Figure 5

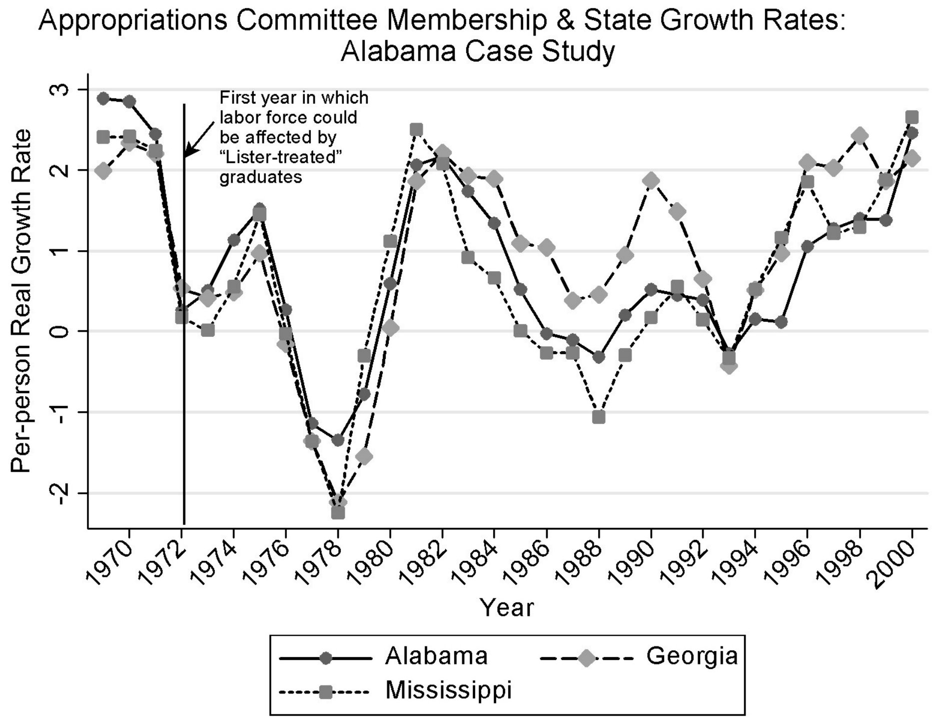

Figure 6

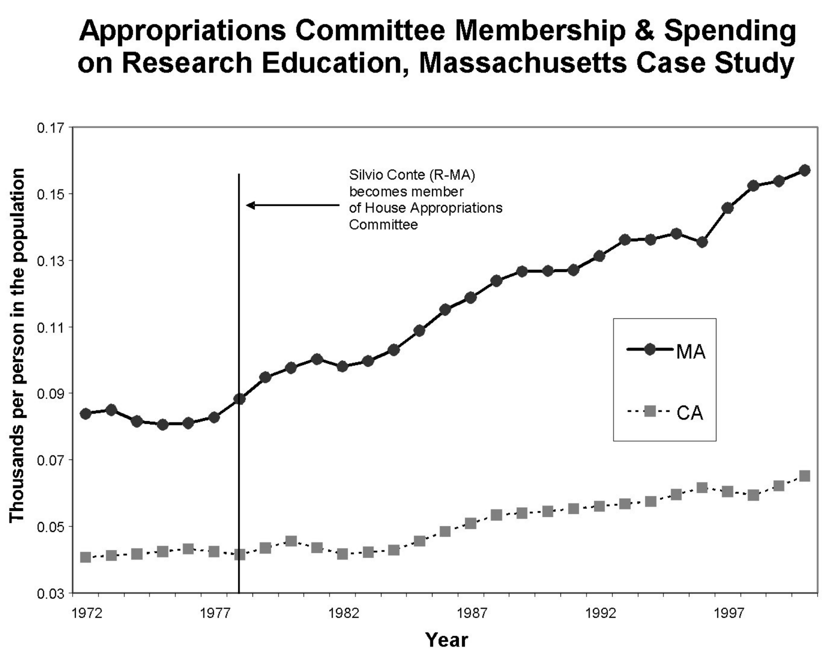

Figure 7

Appropriations Committee Membership & Educational Attainment:
Massachusetts Case Study

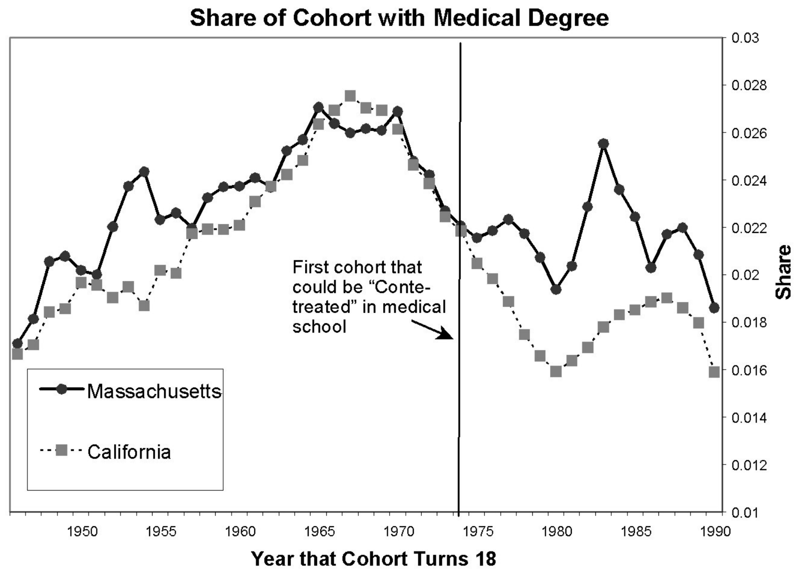

Figure 8

Appropriations Committee Membership & Proximity to the Frontier:
Massachusetts Case Study

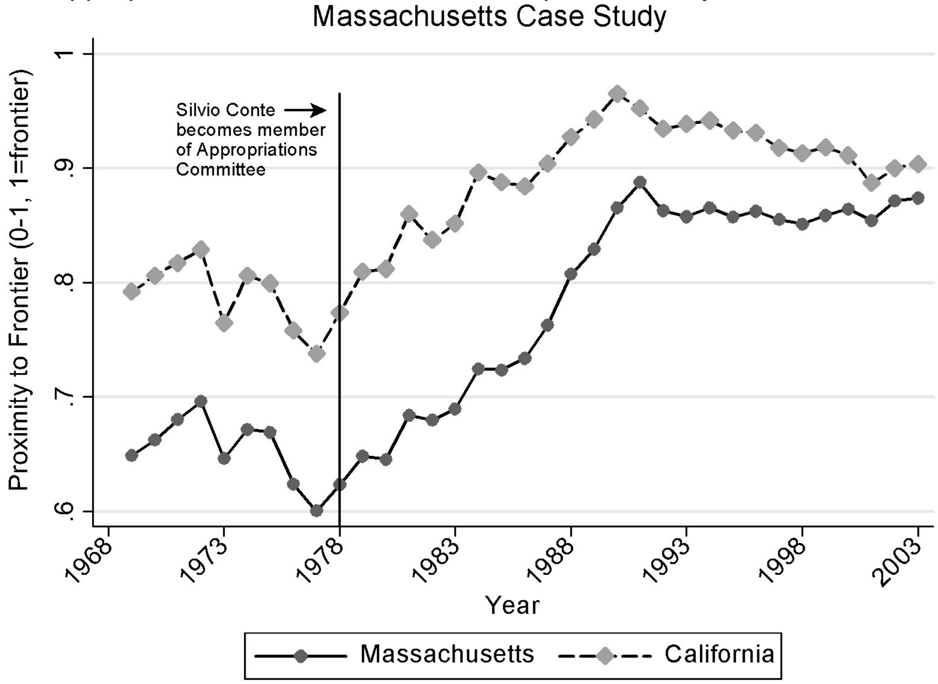

Figure 9

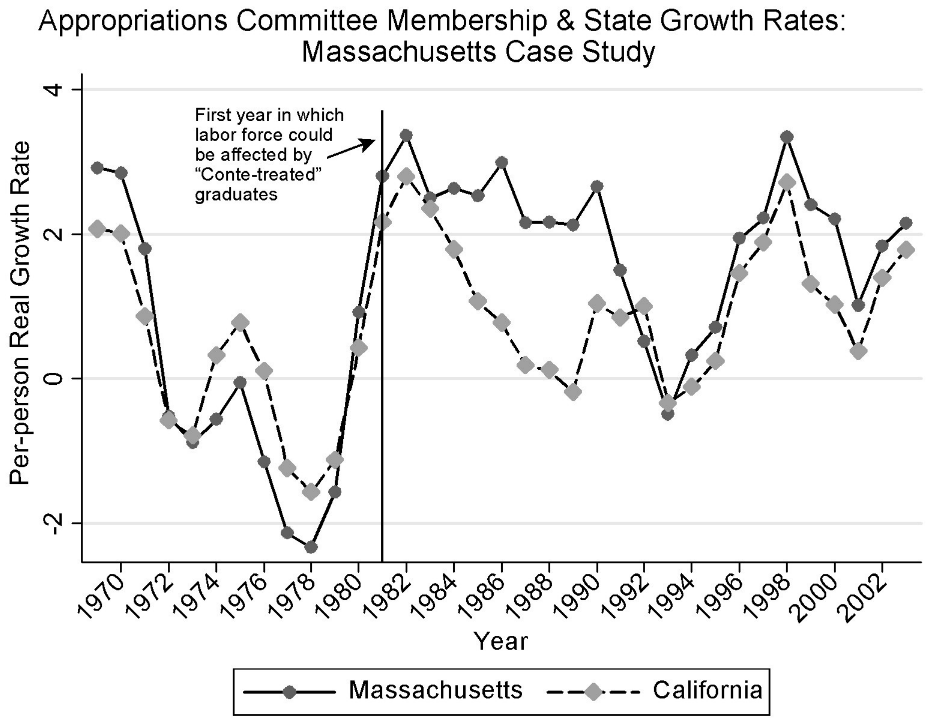
Appropriations Committee Membership & State Growth Rates:
Massachusetts Case Study
Per-person Real Growth Rate
4
2
0
-2
First year in which
labor force could
be affected by
"Conte-treated"
graduates
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
Year
Massachusetts
California

Table 1
The Effect of a Higher Probability of Appointment to the Federal Appropriations Committee on Committee Membership and Expenditure on Research Universities

	Dependent Variable		
	State's Number of Members on Senate Appropriations Committee	State's Number of Members on House Appropriations Committee	Research University Expenditure per Person in the affected cohorts ($2004)
	coefficient [2] (std err)	coefficient [2] (std err)	coefficient [2] (std err)
Independent variables:			
Maximum probability, among state's senators, of appointment to the Senate Appropriations committee[1]	1.33 (0.07)		691.23 (197.18)
Mean probability, among state's congressmen, of appointment to the House Appropriations committee[1]		0.96 (0.20)	347.33 (100.61)
Political control variables: pct. in each party in state & federal legislatures [3]	yes	yes	yes
Instrumental variables relevant to 2- and 4-year college spending (see Table 2)	yes	yes	yes
State indicator variables	yes	yes	yes
Cohort indicator variables	yes	yes	yes
Census Division linear time trends	yes	yes	yes
F-Statistic on the excluded instruments (probabilities of appointment)	564.41	18.13	10.67

Notes:
Ordinary least squares regressions with bootstrapped standard errors (see text). The two regressions shown in the columns to the left are purely for interest. The regression shown in the right-hand column is the implied first-stage regression for research university expenditure.

[1] These probabilities are based on aggregating over the probabilities of individual senators' and congressmen's appointment to their respective chamber's Appropriations Committee. By far the most important predictor of the probability is the state's within-party representation gap on the Appropriations Committee interacted with the arising of a vacancy on the Committee through retirement or death of a member. The within-party representation gap is equal to the percentage of the party in the chamber who are from the state minus the percentage of the party on the committee who are from the state. States can become significantly over- or underrepresented on the Committee through sheer happenstance (another state might have a bigger representation gap at the time a vacancy arises and the opportunity is lost) and through changes in the party make-up of a state's delegation (so that the state hangs onto a Republican committee seat, say, while its growing Democratic party representation gap induces the Democrats to appoint a member). We find that seniority at a time when a vacancy arises plays a minor role. In addition, the state's membership on the other exclusive committees plays a minor role. See text.

[2] Coefficients in bold typeface are statistically significantly different from zero with 90% confidence at least.
[3] The political variables are recorded for each house of the state's legislature and the U.S. (federal) Congress. To ensure that we control for contemporary politics that could have affected education spending other than through committee appointments, we control for the political variables for the 13 years the cohort would typically have been in primary and secondary school (state political variables), the two years they would typically have been in two-year college (state political variables), the four years they would typically have been in four-year college (state political variables), and the four years they would typically have been in graduate school (federal political variables).

For more information on the variables and their sources, see the Data Appendix.

Table 2
The Effect of State Appropriations and Education Committee Chairmen's College Constituencies
on Expenditure at Four-Year Colleges and Universities and at Two-Year Institutions of Higher Education

	Dependent Variable	
	Four-year College/ University Expenditure per Person in the affected cohorts ($2004)	Two-Year College Expenditure per Person in the affected cohorts ($2004)
Independent variables:	coefficient [2] (std err)	coefficient [2] (std err)
number (M) of students enrolled in private four-year colleges and universities in the constituency of the State senate Appropriations committee chairmen[1]	16.3 (4.3)	
number (M) of students enrolled in private four-year colleges and universities in the constituency of the State senate Education committee chairman[1]	2.7 (3.9)	
number (M) of students enrolled in public four-year colleges and universities in the constituency of the State senate Appropriations committee chairmen[1]	28.1 (5.2)	
number (M) of students enrolled in public four-year colleges and universities in the constituency of the State senate Education committee chairman[1]	78.5 (5.3)	
number (M) of students enrolled in private two-year colleges in the constituency of the State senate Appropriations committee chairmen[1]		51.6 (39.0)
number (M) of students enrolled in private two-year colleges in the constituency of the State senate Education committee chairman[1]		42.7 (26.1)
number (M) of students enrolled in public two-year colleges in the constituency of the State senate Appropriations committee chairmen[1]		4.6 (2.6)
number (M) of students enrolled in public two-year colleges in the constituency of the State senate Education committee chairman[1]		19.4 (1.7)
Political control variables: percent in each party in state & federal legislatures [3]	yes	yes
Instrumental variables relevant to research universities (see Table 1)	yes	yes
Controls for the industrial composition and socio-demographics of the chairmen's constituencies	yes	yes
State indicator variables	yes	yes
Cohort indicator variables	yes	yes
Census Division linear time trends	yes	yes
F-Statistic on the excluded instruments (enrollment in constituency)	47.01	44.65

See next page for notes.

Notes:
Ordinary least squares regressions with bootstrapped standard errors (see text).

[1] These enrollment numbers are based on aggregating enrollment in 1980 over all of the relevant institutions of higher education in the county where the senate Appropriations or Education chairman has his home constituency. Senators' constituencies correspond most closely to counties, in most states. In the actual first-stage regressions, we also include enrollment aggregated to the local municipality level and the 3-digit zipcode level, in order to account for those states with oddly-configured Senate geographies. Note that the enrollment numbers are held at the 1980 level so that the enrollment numbers only change because the identify of the chairmen change. See text.
[2] Coefficients in bold typeface are statistically significantly different from zero with 90% confidence at least.
[3] The political variables are recorded for each house of the state's legislature and the U.S. (federal) Congress. To ensure that we control for contemporary politics that could have affected education spending other than through committee appointments, we control for the political variables for the 13 years the cohort would typically have been in primary and secondary school (state political variables), the two years they would typically have been in two-year college (state political variables), the four years they would typically have been in four-year college (state political variables), and the four years they would typically have been in graduate school (federal political variables).

For more information on the variables and their sources, see the Data Appendix.

Table 3
The Effect of Education Investment on Growth (1=1% growth rate)

Independent variables:	dependent var: growth in per cap. income		dependent var: growth in per capita GSP	
	Allowing Migration	Un-doing Migration	Allowing Migration	Un-doing Migration
	coefficient [3] (std err)	coefficient [3] (std err)	coefficient [3] (std err)	coefficient [3] (std err)
Research-type human capital per person[1] (M)	0.01	0.02	0.01	0.02
	(0.02)	(0.02)	(0.02)	(0.02)
4-year college-type human capital per person[1] (M)	0.04	0.04	0.03	0.03
	(0.01)	(0.02)	(0.01)	(0.01)
2-year college-type human capital per person[1] (M)	0.02	0.01	0.02	0.02
	(0.02)	(0.02)	(0.02)	(0.02)
Proximity[2] *Research-type human capital per person[1] (M)	0.06	0.02	0.07	0.03
	(0.01)	(0.01)	(0.01)	(0.01)
Proximity[2] *4-year college-type human capital per person[1] (M)	0.00	0.01	0.00	0.00
	(0.01)	(0.02)	(0.02)	(0.02)
Proximity[2] *2-year college-type human capital per person[1] (M)	-0.01	0.00	-0.02	-0.01
	(0.02)	(0.02)	(0.02)	(0.02)
Primary/secondary human capital & its interaction with proximity	yes	yes	yes	yes
Political control variables[5]	yes	yes	yes	yes
Control for federal spending on highways	yes	yes	yes	yes
Controls for industrial composition and socio-demographics of state chairmen's constituencies	yes	yes	yes	yes
State and cohort indicator variables	yes	yes	yes	yes
Census Division linear time trends	yes	yes	yes	yes
Effects for states midway to the frontier				
Research-type human capital per person[1] (M)	0.04	0.03	0.04	0.04
4-year college-type human capital per person[1] (M)	0.04	0.04	0.03	0.03
2-year college-type human capital per person[1] (M)	0.01	0.01	0.01	0.01
Effects at the frontier				
Research-type human capital per person[1] (M)	0.07	0.04	0.08	0.05
4-year college-type human capital per person[1] (M)	0.03	0.04	0.03	0.03
2-year college-type human capital per person[1] (M)	0.00	0.01	0.00	0.01
Overall R-squared	0.63	0.53	0.60	0.49

See next page for notes.

Notes:
Instrumental variables regressions using generalized methods of moments and bootstrapped standard errors. The dependent variables have, respectively, means of 1.63 and 1.32. They have residual standard deviations of 2.10 and 2.60. The residuals are from state fixed effects, year fixed effects, and Census division time trends. The regression that allows migration relates a state's spending on education to the growth in personal income earned by residents of the state. The regression that un-does migration relates a state's spending on education to the growth in personal income earned by people born in the state (see text).

[1] All human capital variables are in thousands of $2004. They are assembled using education investments and the depreciation schedule described in the text. The education investments are instrumented with political committee variables (see previous tables). The mean human capital stocks are: $22,293 per person in 2-year type education; $73,704 in 4-year type education; $38,283 in research-type education; and $485,996 in primary/secondary education. The corresponding residual standard deviations are: $3115, $2110, $5024, and $60641. The residuals are from state fixed effects, year fixed effects, and Census division time trends.

[2] A state's proximity to the technological frontier is a variable that ranges from 0 to 1. It is set to 0 for a typical far-from-the-frontier state and set to 1 for the state at the frontier. It is based on a state's 1963 patents per dollar of state GDP divided by the maximum value of that variable in any state. The 1963 value is used because later patenting is likely to be endogenous to spending on education. Proximity has a mean of 0.63 and a standard deviation of 0.25.

[3] Coefficients in bold typeface are statistically significantly different from zero with 90% confidence at least.

[4] The political variables are recorded for each house of the state's legislature and the U.S. (federal) Congress. To ensure that we control for contemporary politics that could have affected education spending other than through committee appointments, we control for the political variables for the 13 years the cohort would typically have been in primary and secondary school (state political variables), the two years they would typically have been in two-year college (state political variables), the four years they would typically have been in four-year college (state political variables), and the four years they would typically have been in graduate school (federal political variables).

For more information on the variables and their sources, see the Data Appendix.

Table 4

Specification Checks of the Effect of Education Investment on Growth (1=1% growth rate)

dependent var: growth in per capita income, always allowing migration

	same as left-hand column of Table 3	uniform depreciation of education over 10 years, 30% remains at decade end	uniform depreciation of education over 10 years, 10% remains at decade end	drop political control variables	drop federal spending on highways	drop industrial composition & socio-demographic controls	use proximity based on labor productivity in 1960
Estimated effects							
Effects for states far from the frontier							
Research-type human capital per person[1] (M)	0.01	0.01	0.01	0.01	0.02	0.01	0.02
4-year college-type human capital per person[1] (M)	0.04	0.03	0.05	0.04	0.04	0.05	0.03
2-year college-type human capital per person[1] (M)	0.02	0.01	0.02	0.01	0.02	0.03	0.00
Effects at the frontier							
Research-type human capital per person[1] (M)	0.07	0.06	0.08	0.07	0.06	0.07	0.05
4-year college-type human capital per person[1] (M)	0.03	0.03	0.05	0.03	0.03	0.05	0.02
2-year college-type human capital per person[1] (M)	0.00	0.00	-0.01	0.01	0.00	0.02	-0.02
Primary/secondary human capital & its interaction with proximity	yes	yes	yes	yes	yes	yes	yes
Political control variables[5]	yes	yes	yes	no	yes	yes	yes
Control for federal spending on highways	yes	yes	yes	yes	no	yes	yes
Controls for industrial composition and socio-demographics of state chairmen's constituencies	yes	yes	yes	yes	yes	no	yes
State and cohort indicator variables	yes	yes	yes	yes	yes	yes	yes
Census Division linear time trends	yes	yes	yes	yes	yes	yes	yes

See notes to Table 3.

Table 5
The Effect of Education Investment on Patenting
Dependent variable: Patents per 1000 people in the 25-50 age range

Independent variables:	coefficient [3] (std err)
Research-type human capital per person[1] (M)	0.00
	(0.01)
4-year college-type human capital per person[1] (M)	0.00
	(0.01)
2-year college-type human capital per person[1] (M)	0.01
	(0.01)
Proximity[2] *Research-type human capital per person[1] (M)	0.04
	(0.01)
Proximity[2] *4-year college-type human capital per person[1] (M)	0.02
	(0.01)
Proximity[2] *2-year college-type human capital per person[1] (M)	-0.01
	(0.01)
Primary/secondary human capital & its interaction with proximity	yes
Political control variables[4]	yes
Control for federal spending on highways	yes
Controls for industrial composition and socio-demographics of state chairmen's constituencies	yes
State and cohort indicator variables	yes
Census Division linear time trends	yes
Effects for states midway to the frontier	
Research-type human capital per person[1] (M)	0.02
4-year college-type human capital per person[1] (M)	0.01
2-year college-type human capital per person[1] (M)	0.00
Effects at the frontier	
Research-type human capital per person[1] (M)	0.04
4-year college-type human capital per person[1] (M)	0.02
2-year college-type human capital per person[1] (M)	0.00

See next page for notes.

Notes:
Instrumental variables regressions with bootstrapped standard errors. The dependent variable has a mean of 0.62 and a residual standard deviation of 0.31 (residual from state effects, year effects, and Census division time trends).
[1] All human capital variables are in thousands of $2004. They are assembled using education investments and the depreciation schedule described in the text. The education investments are instrumented with political committee variables. See notes to Table 3 for more detail and descriptive statistics.
[2] A state's proximity to the technological frontier is a variable that ranges from 0 to 1. It is set to 0 for a typical far-from-the-frontier state and set to 1 for the state at the frontier. It is based on a state's rank in labor productivity in 1960. The 1960 value is used because later labor productivity is likely to be endogenous to spending on education.
[3] Coefficients in bold typeface are statistically significantly different from zero with 90% confidence at least.
[4] The political variables are recorded for each house of the state's legislature and the U.S. (federal) Congress. To ensure that we control for contemporary politics that could have affected education spending other than through committee appointments, we control for the political variables for the 13 years the cohort would typically have been in primary and secondary school (state political variables), the two years they would typically have been in two-year college (state political variables), the four years they would typically have been in four-year college (state political variables), and the four years they would typically have been in graduate school (federal political variables).

For more information on the variables and their sources, see the Data Appendix.