University Research and the Market for Higher Education*

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Abstract

This paper develops a framework in which university research depends endogenously on competition for tuition and talented students in the market for higher education. When students are highly stratified across colleges, or when tuition rises sharply with school rank, universities spend on R&D even if the direct contribution of research to teaching is small. The model is consistent with causal evidence and matches new features of the microdata. It explains why universities internally fund research with tuition, despite negligible returns to patenting. Calibrated simulations suggest that existing tuition policies boost university research while research subsidies crowd it out.

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1 Introduction

The modern research university is a unique and complex institution. While primarily focused on higher education, universities also contribute to the advancement of knowledge through investment in research. Between 2000 and 2018, universities in the United States accounted for 13% of aggregate spending on research and development (R&D) and 53% of all spending on basic scientific research. Discoveries arising from university research contribute to innovation in nearly every field of science and have given rise to numerous general purpose technologies that drive long-run growth.

The coincidence of education and research within the university has multiple historical and economic roots which have been analyzed in the literature. Early American universities–especially land grant colleges–were established explicitly to provide training and conduct research that would benefit their local economy. During World War II, the federal government drastically increased funding for university research to support the war effort. The success of these war-time partnerships gave rise to the modern system of publicly funded university research.[1] While initially focused on defense, by the 1970s the federal government accounted for over 75% of university R&D funding with projects spanning healthcare, energy, and the environmental sciences. By the 1980s, patenting and the commercialization of academic research–made possible in part by the Bayh-Dole Act–emerged as important catalysts in select areas of university research, such as the biomedical and pharmaceutical sciences.

This paper proposes an additional determinant of university research which stems from its objectives in education markets. It develops a model in which university research depends on the competition for tuition and talented students in the market for higher education. By spending on research, universities improve the quality of education they offer prospective students. Students benefit directly from research at their university by being

[1] The case for the modern system of publicly funded academic research after World War II is famously articulated in Vannevar Bush's (1945) *Science: The Endless Frontier*.

exposed to frontier knowledge and scientific techniques. They also benefit indirectly, as top research universities attract wealthier and higher ability students, who further augment education quality through peer effects and higher spending. Consequently, incentives for university research–and the resources available to undertake it–depend on the competition for tuition and talented students.

The model rationalizes why universities fund research with tuition revenue and quantitatively matches its extent in the data.[2] It explains why universities continue to spend internal funds on research despite consistently low returns to patenting. In 2018, over 25% of university research expenditure was funded internally, while between 1991 and 2018 the median university earned patent royalties totaling less than 2% of their expenditure on research.[3] The model also quantitatively replicates the joint distribution of university education and research outcomes, capturing the fact that universities which spend more on R&D are higher ranked, attract wealthier and more able students, and charge higher tuition.

By exploiting a natural experiment, the paper provides causal evidence in support of the model's core mechanism. A key feature of the framework is that investing in research enables a university to charge higher tuition in the future. To assess this channel, we employ plausibly exogenous variation in university R&D created by a rapid doubling of the National Institute of Health's (NIH) research budget between 1998 and 2003. We instrument the change in each university's R&D during this period with a Bartik-style instrumental variable constructed using the share of all federal life science research grants they were awarded just prior to the NIH funding expan-

[2]While universities may spend on research because they care about research per se, there is still the question of how they fund such spending. The mechanism here provides an *endogenous* motivation for universities to spend on research and rationalizes why–in a competitive higher education sector–students would allow universities to divert tuition revenue to support research activities.

[3]The share of internally funded university R&D has also grown drastically relative to publicly funded R&D. While the share of publicly funded university R&D fell from around 75% in the 1970s to just over 50% today, over the same period the share of internally funded university research grew from 10% to 25%. Section 2 provides further details.

sion. Consistent with the model's core mechanism, the benchmark specification shows that universities may recoup up to 15% of R&D expenditures through increased tuition.

We formalize the theory by jointly modelling university instructional and research expenditures in a general equilibrium model of the higher education sector. The model builds on existing equilibrium models of higher education, such as Epple, Romano, and Sieg (2006) and Cai and Heathcote (2022), by endogenizing university R&D decisions alongside their pedagogical ones. Universities are endogenously differentiated in their stock of knowledge–a form of institution-specific intangible capital that universities accumulate by investing in research–which they impart to students.[4] This knowledge, together with student peer effects, teacher quality, and spending on instructional equipment determines the quality of education a university offers. An important theoretical contribution of this paper is to show that there exists a dynamic equilibrium with quality maximization and an endogenous college quality hierarchy in this class of models.

A key purpose of the model is to demonstrate the interdependence of university research and education outcomes. Equilibrium in the market for higher education features an endogenous hierarchy of colleges differing in education quality, with two-dimensional sorting of students by ability and family income. University intangible capital induces an ordering among institutions which influences their position in the hierarchy of colleges. Those higher-up in the hierarchy charge higher tuition and attract better students and faculty. By spending on research, universities are able to improve their position in the hierarchy. The greater the positive sorting of students to schools, and the more tuition rises with college rank, the stronger is the incentive for universities to spend on research. Importantly, universities face incentives to spend on research when students are highly stratified across

[4]The intangible capital created by research primarily includes frontier knowledge and ideas. Exposure to frontier knowledge has been shown to improve education quality and the human capital and earnings of graduates (Biasi and Ma 2021). More broadly it also represents professional networks, industry recruiting, and access to advanced labs, computing, scientific methods.

colleges, even if the direct contribution of research to teaching quality is small. Conversely, the incentive to spend on research is diminished if universities are ex ante highly unequal, since top schools face weaker incentives to invest in enhancing their position while lower-ranked institutions find it too costly to invest in improving their rank.

The model has two important implications for public policy. First, current federal need-based student aid programs increase university R&D expenditures by 8.1%. The effect is driven in part by the impact of need-based student aid on the nature of competition between colleges. Since children from poor families disproportionately attend lower quality schools, progressive tuition subsidies redistribute financial resources and shrink the dispersion in financial resources across schools. As a result, colleges become more similar to one another in the long-run, increasing their incentive to spend on research to differentiate themselves from competing institutions.

Second, the model predicts that current federal research grants crowd out private university spending on research and increase educational inequality by concentrating resources at top schools. The calibrated model predicts that public R&D grants boost university research by 69.1%, which is 6.9 percentage points below the government's share of university research funding. The crowding-out of internal university research spending occurs because the concentration of federal R&D funding at top schools makes it too costly for lower-ranked institutions to compete effectively through research. The model predicts that replacing the status-quo system with a flat R&D subsidy would boost university research expenditure by 14.8% by reducing the cost of research while preserving competition between schools.

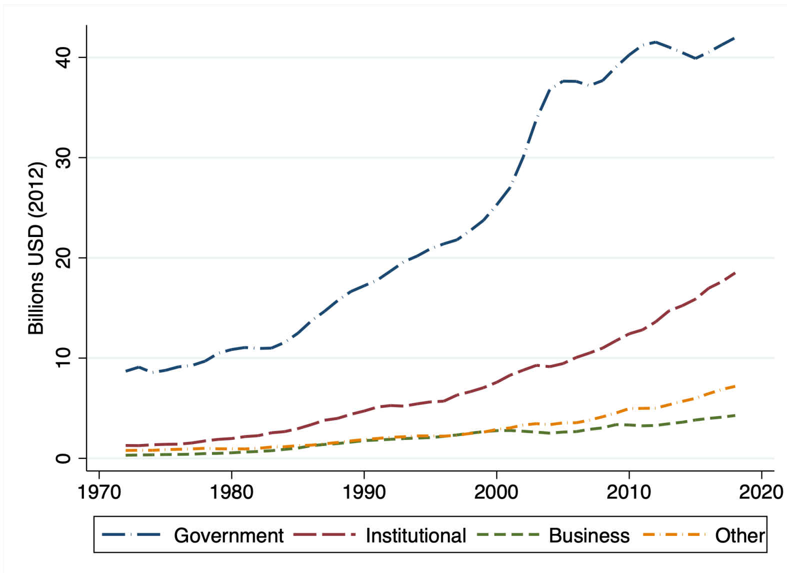
This paper contributes to the economics of science and in particular the literature on university R&D (Merton 1973; Jaffe 1989; Rosenberg and Nelson 1994; Stephan 1996; Rothaermel, Agung, and Jiang 2007; Mowery et al. 2015). It identifies additional incentives for university research which depend endogenously on the market for higher education. The mechanism helps explain the joint distribution of university research and teaching outcomes, highlighting new channels through which scientific innovation and education policies may interact (Biasi, Deming, and Moser 2020; Akcigit, Pearce, and Prato 2020). By analyzing the university's incentives to conduct research, the paper also complements work in a related literature examining the research incentives of individual faculty (Lach and Schankerman 2008; Azoulay, Graff Zivin, and Manso 2011; Hvide and Jones 2018).

This paper also contributes to the literature studying basic research and the optimal provision of public R&D subsidies (Akcigit, Hanley, and Serrano-Velarde 2020; Akcigit, Hanley, and Stantcheva 2022). The standard view in the literature is that basic research, while socially valuable, is subject to imperfect property rights which prevent the full appropriation of the returns to new discoveries. Public subsidies are necessary since firms have little incentive to invest in basic scientific breakthroughs that others can cite and build-on (Nelson 1959; Arrow 1962; Rosenberg 1990). An important insight of this paper is that universities appear to have private incentives to undertake basic research and, in practice, do most of it. As a result, the need for government subsidies to basic R&D could be less than previously thought.

2 Research in the Higher Education Sector: Stylized Facts

In this section, we document four important facts on the market for higher education and university research. First, while the government is an important source of research funds, over one-quarter of university R&D is paid for with internal funds. Second, while patenting is the traditional explanation for why firms spend on research, patent licensing revenue at universities appears too small to be the primary driver of their internal R&D spending. Third, universities which spend more on R&D also deliver higher quality education, admit higher ability students, produce more scientific output, and charge higher tuition. Finally, we provide causal evidence from a natural experiment on the NIH, that spending on R&D enables universities to charge higher tuition. Details on the data sources and notes on figures are contained in appendix A and additional figures in appendix B.

Figure 1: University Research Spending by Source of Funds



2.1 University R&D: Stylized Facts from Administrative Microdata

The first important fact is that a large share of university research is financed using internal funds. Figure 1 plots the major sources of university research funds going back to 1972.[5] While it confirms the well-known fact that the federal government is the largest source of funds for university research, accounting for 52.97% of all funding in 2018, it also shows that internal institutional funds are the second largest source, accounting for 25.54% of total funding. The remaining research funds come predominantly from state and local governments and sponsored research activities funded by private corporations and non-profit institutions.[6]

[5]The underlying Higher Education R&D (HERD) survey includes 916 universities representing 99.1% of the total R&D expenditure of the higher education sector and roughly 80% of FTE students. Before 2010, it includes only institutions with degree programs in science and engineering, and at least $150,000 in separately accounted for R&D expenditures.

[6]Specifically, state and local governments account for 5.46%; non-profit organizations accounts for 6.89%; private corporations accounts for 5.97%; and the final 3.17% from non-categorized sources.

How do universities fund their internal spending on research? From the perspective of paradigmatic models of R&D at private firms, this spending should be financed by the patent revenue universities derive from their scientific discoveries.[7] However, despite many high profile anecdotes to the contrary, the data show that university revenue from patent licensing is far too small for this to be the case. Figure 2 displays the distribution of gross patent licensing revenue over total research expenditure at the university level. Between 1991-2018, the median university earned combined licensing fees totaling less than 2% of their expenditure on R&D. The size of these income streams means that patenting cannot account for the majority of internal university spending on research.[8] Without direct revenue from patents, universities must fund their internal spending on R&D using other sources of unrestricted operating funds – which in practice is composed almost entirely of tuition revenue (Council on Government Relations 2019).[9] The internal resources available for university research therefore depend, in a direct accounting sense, on the tuition revenue they take in from students.

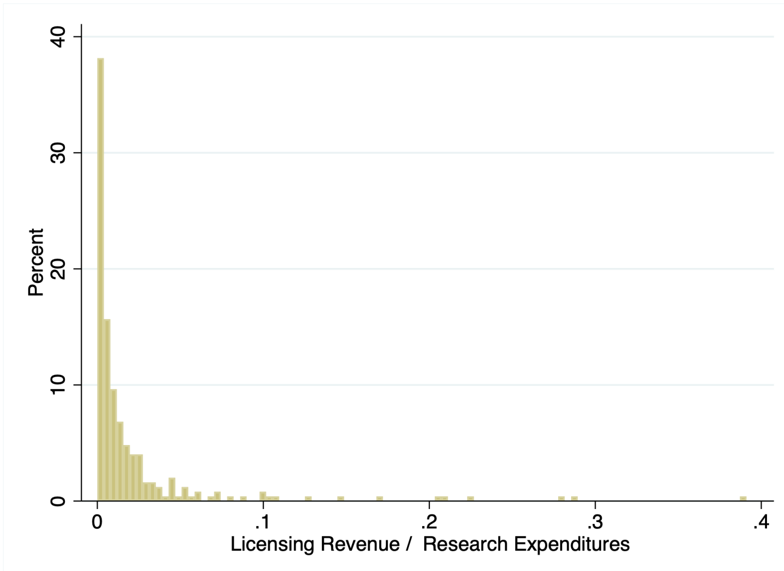
A key question then is why – in a highly competitive higher education sector – do universities divert tuition to support research and students willing to pay for that? The answer developed in the model below is that university research activities contribute to education quality, increasing students'

[7]This view is also consistent with the literature showing that individual faculty research output increases with additional ownership over their scientific discoveries (Lach and Schankerman 2008; Hvide and Jones 2018). However, the focus here is on the incentives of the university – not faculty – and in particular how university research is financed.

[8]The finding is consistent with the literature showing that past expansions in university patenting rights (e.g. the Bayh-Dole Act) have had only negligible effects on aggregate university R&D (Mowery et al. 2015). Of course, while these data appear to preclude patents as the primary driver of internal university R&D spending, they do not rule out the possibility that patenting is an important incentive for individual faculty researchers and certain sub-fields of R&D, such as biomedical life sciences.

[9]In practice, the largest dependence of research expenditure on tuition revenue comes from recurring facilities and administration (F&A) costs associated with sponsored projects that are not reimbursed by the negotiated indirect cost rate. Colloquially, these costs include the persistent maintenance and administration costs of labs used to conduct sponsored research for government, private, and non-profit institutes. For example, in 2018 roughly $7 billion of internal university research expenditure was due to cost-sharing and unrecovered F&A costs associated with sponsored research projects.

Figure 2: University Patent License Revenue over Research Expenditures

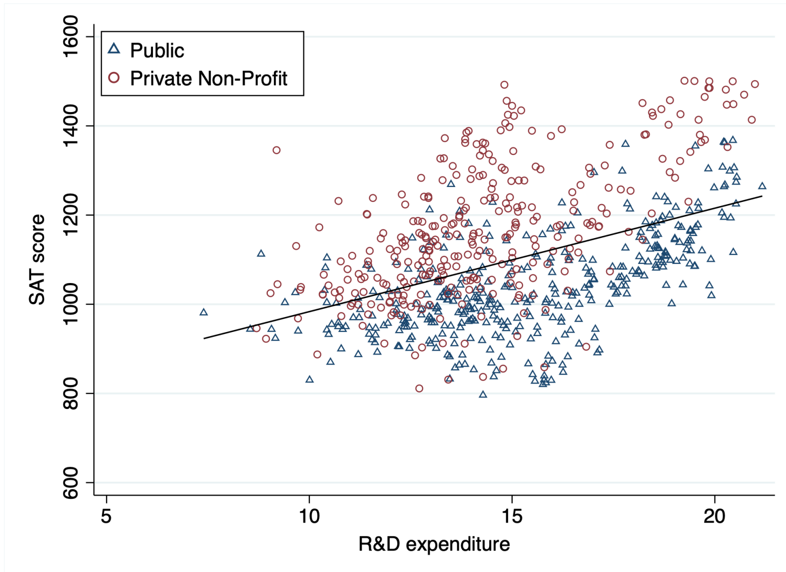


willingness to pay. Consequently, universities have endogenous incentives to spend on R&D which stem from the education market. Moreover, when students are highly stratified across colleges, or when tuition rises sharply with college rank, universities can have strong incentives to spend on R&D even if the direct contribution of research to teaching is small.

In support of this mechanism, the final stylized fact documents a strong correlation between a university's research spending, its tuition rate, and its position in the hierarchical market for higher education. The most important of these indicators, from the perspective of the model, pertains to the distribution of tuition revenues and the sorting of high ability students across colleges.[10] Using SAT scores as a proxy, Figure 3 shows that schools which spend more on research are also attended by higher ability students. In the presence of peer-effects, this positive sorting augments the contribu-

[10]Universities which spend on research also employ better paid faculty (Figure B2), produce more impactful scientific output (Figure B3), and consistently appear at the top of the rankings of best colleges (Table C1).

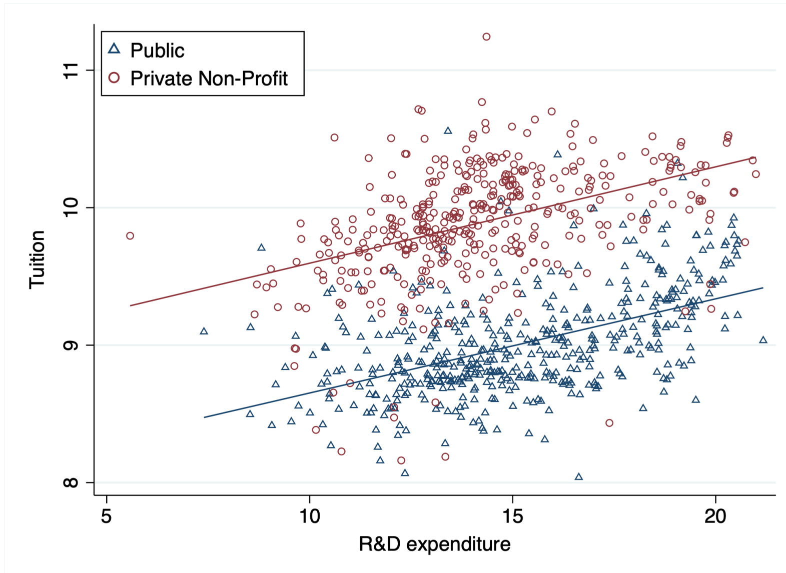
Figure 3: University Research Spending and Student Ability, by Sector



tion of research expenditure to education quality. As a result, even if the *direct* contribution of R&D to teaching small, universities may still spend on R&D simply to attract the best students. Similarly, Figure 4 shows that universities which spend the most on R&D are also those who charge the highest tuition.[11] The positive correlation can be interpreted as evidence that households recognize the value of university research and are willing to pay higher tuition to attend schools which spend on it. In the model, we formalize the relationship between the magnitude of this correlation and the strength of incentives for universities to spend on research.

[11]The level difference in tuition between public and private non-profit universities can be largely attributed to state and local appropriations, much of which serve as tuition remission. Figure B4 plots the relationship between tuition and R&D when we include state and local appropriations in tuition and shows that cross-sectional elasticity remains largely unchanged. Figure B5 shows the patterns also do not appear to be driven by differences in student amenities, as proxied by student services expenditures.

Figure 4: University Research Expenditure and Tuition, by Sector



2.2 The Impact of R&D on Tuition: Evidence from a Natural Experiment

The previous section provides suggestive evidence that by investing in research, universities can charge higher tuition and attract better students. This section provides estimates of the causal effect of R&D on university tuition. The quasi-natural experiment exploits a large increase in federal research funding through the National Institute of Health (NIH). Between 1998 and 2003, the federal government doubled the NIH budget for biological and life sciences research from $13.6 billion in 1998 to $27.1 billion in 2003 (Smith 2006). The NIH expansion accounts for most of the rise in federal funding for university research during this period, and its impact on total spending is clearly visible in the aggregate time series (see Figure 1).

To capture the exogenous variation in university R&D created by the policy change, we construct a Bartik style shift-share instrument by computing the share of all federal research grants and contracts for life sciences research that each university won in the period preceding the doubling of the NIH budget. As an instrument, the shares are relevant since the NIH constituted the bulk of federal funding for university life sciences research even before the policy change and it did not substantially change the award criteria after the budget increase. The shares are also exogenous provided universities did not systematically invest in life sciences research in the pre-period in anticipation of the NIH budget expansion. Our identification strategy is similar to Azoulay et al. (2019), but at a coarser institutional level.

We estimate the causal impact of an increase in university R&D on its tuition growth by employing the following reduced-form econometric model of the mechanism we introduce in the next section. Denoting the tuition of university i at time t by y_{it}, we model its relationship to university R&D with the following set of simultaneous equations,

$$y_{it} = a_i + \mathbf{D}_g \times \mu_t + \boldsymbol{\gamma}_1 \, \mathbf{D}_s \times \mathrm{K}_{it} + \gamma_2 \, \mathbf{X}_{it} + \nu_{it}$$

$$\mathrm{K}_{it+1} = b_i + (1-\delta)\mathrm{K}_{it} + \lambda_1 \, \mathrm{RD}_{it} + \lambda_2 \mathbf{X}_{it} + \eta_{it}$$

where a_i and b_i are university fixed effects, μ_t are time fixed effects, D_s is a vector of sector (public and private) indicators, D_g is a vector of group-specific indicators, and X_{it} includes covariates. The variable K_{it} represents the university-specific intangible capital created by its research activities, which depreciates at rate δ. Parameter $\boldsymbol{\gamma_1}$ captures the extent to which K_{it} improves education quality and hence the school's desirability to students and their willing to pay higher tuition. The second equation captures the fact that universities can increase this intangible capital by spending more on research, RD_{it}.

The D_g indicators control for group-specific time trends in tuition that may be confounded with the instrument. In particular, the design allows for different time trends for public versus private universities and for universities which were engaged in life sciences research (NIH funded or otherwise) before the policy intervention. It also allows for tuition trends to differ across school size, to capture economies of scale, and by initial school quality, proxied by its faculty-to-student ratio. The D_s indicator additionally allows the marginal effect of R&D on tuition to differ at public and private universities.

To exploit the exogenous policy variation, we estimate the model in long-differences, comparing steady states before and after the doubling of the NIH research budget. We instrument the increase in university R&D over this period using the shares of federal life sciences funding they were awarded before the policy change and measure its impact on the growth in tuition.[12] Combining the system of equations above, we estimate

$$\triangle y_i = \bar{\boldsymbol{\mu}}_g + \beta_1 \triangle \mathrm{RD}_i + \beta_s \mathrm{D}_s \times \triangle \mathrm{RD}_i + \beta_2 \triangle \mathbf{X}_i + \epsilon_i \tag{1}$$

where β_1 is the main parameter of interest, capturing the net impact of R&D on tuition through λ_1 and γ_1. The $\bar{\boldsymbol{\mu}}_g$ captures group-specific time trends in tuition during the treatment period. The dependent variable $\triangle y_i$ is the change in university i's net tuition from 1993-1997 to 2004-2008. The federal life sciences grant shares used as instruments are calculated with respect to the same pre-period, 1993-1997. The main independent variable, $\triangle \mathrm{RD}_i$, measures the change in each university's R&D expenditure per student before and after the NIH research budget expansion. All regressions use robust standard errors, clustered at the state level, and allow for state-specific time trends in tuition to control for changes in state level tuition policies.

The first column of Table 1 reports the estimation result of the specification in (1) controlling only for state specific tuition trends. The results show that universities with the largest exogenous increase in R&D expenditure are also those with the largest increase in tuition. The effect is statistically significant and the magnitude of the effect is economically substantial: a $1.00 increase in university research spending per student leads to a $0.15 increase in tuition per student. In other words, the estimate suggests that universities may recoup 15% of their R&D spending through higher tuition.

[12] Ideally, these exercises would include additional specifications to measure the exogenous impact of research on subsequent student ability as well. Unfortunately, this is not possible given that our data only reports proxies for student ability beginning after the NIH policy intervention.

Table 1: Estimated Causal Effect of University R&D Spending on Tuition

	(1)	(2)	(3)	NLA	LAC	Placebo
R&D Expenditure (β_1)	0.15	0.10	0.10	0.12	4.04	3.82
	(0.05)	(0.03)	(0.05)	(0.05)	(16.22)	(2.79)
R&D $\times$ Private Non-Profit (β_s)		0.06	0.06	0.05	-3.97	-1.25
		(0.07)	(0.07)	(0.07)	(16.25)	(3.06)
Private Non-Profit University (μ_g)		2.81	2.88	3.17	3.81	1.37
		(0.37)	(0.36)	(0.43)	(1.50)	(3.09)
number of observations	1,565	1,565	1,562	1,062	503	1,565
R-squared	0.17	0.41	0.42	0.44	0.48	-
state trend fixed effects	yes	yes	yes	yes	yes	yes
pre-trend characteristic controls	no	no	yes	yes	yes	yes

Notes: *The coefficients in the table report the estimated causal impact of a $1 increase in university research spending per student on tuition per student in model (1). All regressions are weighted by university size, measured by their initial number of full-time equivalent (FTE) students. Sector tuition fixed effect μ_g reported in $1000s. Parenthetical values report robust standard errors clustered at the state level. Pre-trend controls include initial university size, full time faculty-to-student ratio, and life science research status in 1987-1992.*

Column (2) investigates the extent to which the effect of research differs across public and private non-profit institutions. One concern is that public universities may face additional constraints in setting tuition and admitting students that can affect their ability to capture the returns to R&D compared with private universities. To address this, column (2) reports estimates that allow the effect of R&D and the trend growth in tuition to differ at public and private universities. The average effect of R&D on tuition continues to be highly significant, though slightly smaller. While the point estimates may suggest that the effect of research spending on tuition may be 60% stronger at private non-profit institutions compared to public universities, the effect is not statistically significant.

One limitation of the empirical design is that the NIH expansion occurs at a common point in time for all universities, which means it may be correlated with other market changes unfolding simultaneously. For instance, it is possible that initially larger or better quality research universities experienced larger tuition increases for reasons that may be unrelated to R&D or the NIH shock. To mitigate these concerns, column (3) adds controls to the first-differences specification in (1) which allow the change in tuition during our sample period to depend on pre-existing differences in university education quality, research composition, and economies of scale. These initial characteristics (1987–1992) include a university's full-time faculty-to-student ratio, the initial size of its student body (FTE), and an indicator identifying institutions that were engaged in life science research even before the NIH intervention.[13] The results in column (3) show that controlling for these initial differences leaves the main estimates largely intact.

As an additional test, columns four and five compare the impact of the NIH expansion on tuition at liberal arts colleges and research universities. To be consistent with the interpretations above, we expect the results for research universities to be stronger than those for liberal arts colleges – where research is less of a focus. To accomplish this, we partition our sample and re-estimate the full model in (3) on the sub-populations of liberal arts (LAC) and non-liberal arts (NLA) research universities.[14] In line with earlier interpretations, the results in Table 1 show that the aggregate effect of the NIH expansion is driven by research universities. The NIH shock did not have a statistically significant effect on tuition at liberal arts college, while the estimated effect on tuition at research universities continues to be highly significant with an even larger point estimate.[15]

[13]Unfortunately, many of the variables in our data do not go back far enough to provide a more complete set of pre-trend tests and controls of the long-differences specification.

[14]Unlike Land Grant Colleges, Tribal Schools, or Historically Black Colleges and Universities (HBCUs) – "Liberal Arts College" is not a Congressional designation. As a result, there is no official definition in the NCES administrative data that allows us to identify these types of institutions. To overcome this challenge, we focus on institutions that self-identify as liberal arts colleges, using Wikipedia's dynamic list of liberal arts colleges in the United States: https://en.wikipedia.org/wiki/List_of_liberal_arts_colleges_in_the_United_States. We manually match these colleges to the NCES sample using name and location reported on their linked Wikipedia pages. The procedure identifies just over 32% of the institutions in our sample as liberal arts colleges, enrolling roughly 24% of FTE students at the start of our sample.

[15]An important caveat is that the regression on liberal arts colleges may not have suffi-

The final column of Table 1 reports the results of a placebo test of our instrumental variable strategy and empirical design. In reality, universities spend on a variety of inputs to make their institution appealing to prospective students. If our results are driven by spurious correlations across these many spending categories – rather than the effect of research itself – we would expect to find similar effects when substituting these alternative expenditures for research spending. To conduct this placebo test, we replace university research spending with spending on student amenities and re-estimate the full model in column (3). Spending on student amenities comes from the same NCES IPEDS accounting framework, and is constructed in the same manner, as the original research variable.[16] The results of the placebo test reject the conjecture that our results are driven by spurious correlations across university spending categories, showing no statistically significant effect.

3 Model of University R&D in the Higher Education Sector

We develop a general equilibrium model of the higher education sector with heterogeneous universities that engage in teaching and research while competing for talented students and tuition revenue. In each generation, heterogeneous households decide which college their children will attend. Colleges choose the pool of students to admit and how to allocate resources between teaching and research activities.

cient power. This is because the sub-sample of liberal arts colleges is both much smaller than that of research universities (see previous footnote) and also much more heterogeneous. For instance, the LAC sample includes premiere institutions which operate much like small research universities (e.g. Williams, Swarthmore), but also many smaller institutions pursuing idiosyncratic religious or public-good missions.

[16]Specifically, the placebo variable is changes in spending on student services per capita before (1993-1997) and after (2004-2008) the NIH expansion. The NCES documentation defines student services expenditure to encompass those activities "...whose primary purpose is to contribute to students emotional and physical well-being and to their intellectual, cultural, and social development outside the context of the formal instructional program. Examples include student activities, cultural events, student newspapers, intramural athletics, student organizations, supplemental instruction outside the normal administration, and student records. Intercollegiate athletics and student health services may also be included except when operated as self - supporting auxiliary enterprises."

3.1 Households

The economy is populated by overlapping generations of dynasties indexed by $i \in [0,1]$. Each period corresponds to one generation. At time t, a household of dynasty i is characterized by the parents' human capital (h_{it}) and the human capital of their child at the end of high school (z_{it}). Households choose consumption (c_{it}) and a college quality for their child (q_{it}), which will determine their human capital as an adult. When no confusion results, we drop the subscripts and denote the state variables of the next generation with a prime " ′ ". Letting β represent the intergenerational discount factor, the household objective can be formulated recursively as

$$U(h,z) = \max_{c,q} \left\{ \ln(c) + \beta \mathbb{E}\left[U(h',z')\right] \right\} \tag{2}$$

subject to the household budget constraint

$$c + p(q,z) = wh \tag{3}$$

where w is the exogenous effective wage rate and $p(q,z)$ is the endogenous tuition schedule determining the cost of sending a student of ability z to a college of quality q. Upon graduating college, children become adults and enter the labor market with human capital h' that depends on the quality of college they attended and their pre-college ability,

$$h' = zq^{\alpha} \tag{4}$$

where α parameterizes the earnings elasticity with respect to college quality. We assume student ability z is known to both households and colleges and i.i.d. log-normally distributed $\ln z \sim \text{i.i.d.}\, \mathcal{N}\left(-\sigma_z^2/2, \sigma_z^2\right)$ where σ_z^2 is the population variance of student ability.

3.2 Universities

There is a unit mass of heterogeneous colleges indexed by $j \in [0, 1]$. We assume that all colleges are of the same size and each admits a continuum of heterogeneous students. The primary activity of a college is to educate its students. The quality of education (q) a college offers depends on its teaching expenditure per student (e_T), a student peer effect ($\bar{z}$), and the university's intangible capital (k). Formally,

$$q = k^{\omega_k} \bar{z}^{\omega_z} e_T^{\omega_e} \tag{5}$$

where ω_x parameterizes the elasticity of college quality with respect to input x. As in Cai and Heathcote (2022) we assume the technology exhibits constant returns to scale so that the size of a college is irrelevant.

The direct dependence of education quality on a university's intangible knowledge through ω_k represents the value of exposing students to frontier ideas and methodologies. Biasi and Ma (2021) provide micro-econometric evidence suggesting that $\omega_k > 0$, since universities which include more frontier knowledge in their academic curricula produce better educational outcomes, including higher earnings for their graduates. In our model, such knowledge capital is a by-product of academic research. Universities spend on R&D in part to accumulate this intangible capital that improves the quality of education they can deliver to students.[17] Formally, the law of motion for knowledge capital is given by,

$$k' = k^{\gamma_k} e_R^{\gamma_e} \tag{6}$$

[17] While we maintain the perspective that research improves education through the discovery of new knowledge, or building expertise among faculty, the model is consistent with alternative interpretations for how a university's spending on research augments its education quality, such as through reputation effects, network effects, or other forms of intangible capitals. The extreme case where intangible knowledge doesn't increase human capital but only act as a signal of the institutions' reputation, facilitating job placement, would correspond to the limiting case $\omega_k \to 0$. Even in this case universities conduct research in equilibrium to signal their quality (see Section 4.2) and a robustness exercise shows that our results are of the same order of magnitude (see Section 6.3).

where e_R is university expenditure on research and $\gamma_k < 1$ captures the notion that a knowledge capital is persistent, but depreciates over time.[18]

Finally, consistent with a wealth of empirical evidence, we allow the peer effect within a university, $\bar{z}$, to depend on student heterogeneity in both ability and socioeconomic background,[19] so that:

$$\ln \bar{z}(\phi; p) = \mathbb{E}_{\phi(.)}[\ln(z)] - \sigma_u^2(\phi; p). \tag{7}$$

The first term captures ability peer effects using a geometric average of student abilities within the college, where $\phi(.)$ denotes the endogenous distribution of abilities among the students admitted by the university. The second term, $\sigma_u(\phi; p)$, represents the indirect costs of socioeconomic heterogeneity in the student body. It captures the idea that the more heterogeneous the class in terms of student ability and economic background, the more difficult it is for a college to deliver a given education quality to its students. This is supported by empirical evidence showing that a very heterogeneous classroom can make peer interactions and teaching harder (Figlio and Page 2002; Duflo, Dupas, and Kremer 2011). We model σ_u^2 as the within-college variance of a weighted average of (log) tuition $\sigma_u^2(\phi; p) = \frac{\Omega}{2} V_{\phi(.)}(\ln p(q, z))$ where Ω is an aggregate constant defined in equation (43) in Appendix F. Defining σ_u^2 in this manner transforms the arithmetic average of tuition into a geometric one which ensures that the equilibrium assignment rule which governs the sorting of students across colleges is log-linear.[20]

[18]We are not the first one to use a multiplicative law of motion for knowledge, see for example Hall and Hayashi (1989) and Klette (1996). The technology can be extended to allow for the slow diffusion of research discoveries across colleges. Higher levels of diffusion generally reduce the university's private incentive to invest in R&D. We omit detailing this process due to a lack of good data to discipline its importance. Instead, we capture these effects through the more general depreciation factor γ_k.

[19]See Epple and Romano (2010) and Sacerdote (2014) for a review of the empirical literature on peer-effects. The importance of these effects motivated early approaches to modelling universities as "club goods", see Epple and Romano (1998).

[20]This term is instrumental in ensuring that the model remains tractable. Without it, the

Following the literature, we assume colleges value the quality of education they deliver to their students as in Epple, Romano, and Sieg (2006) and behave competitively as in Cai and Heathcote (2022). We extend these static frameworks by including a research investment decision that makes the university problem dynamic. A natural extension is to assume that colleges value the discounted sum of the quality of education offered to current and future students. Letting the instantaneous flow payoff for a college delivering education of quality q be $\ln q$, the university problem can be formulated recursively as

$$V(k) = \max_{\phi, e_T, e_R} \ln q + \beta V(k') \tag{8}$$

subject to the education technology in (5), the research technology (6), the peer effect (7), and a flow budget constraint given by

$$\mathbb{E}_{\phi(.)}[p(q,z)] = e_R + e_T \tag{9}$$

where e_R and e_T are university research and teaching expenditures, respectively, and $\phi(z)$ represents the composition of the admitted student body as a density of student ability z. The university's tuition revenue, $\mathbb{E}_{\phi(.)}[p(q,z)]$, is determined by the quality of education it offers, the composition of its student body, and the equilibrium tuition schedule $p(q,z)$.

Importantly, while both teaching and research expenditure will increase education quality, university research plays an additional role. The intangible capital k' produced by research induces an ordering among institutions which shapes the hierarchy of colleges that prevails in equilibrium. Universities which are higher on the ladder of colleges can charge more tuition and attract better students, further augmenting the quality of education they offer.

While this section abstracts from government policies and the spillovers

tuition schedule and the assignment rule wouldn't be log-linear. As a result, one would lose the linearity of the laws of motion of the mean and standard deviation of the equilibrium distribution of (log) human capital as well as the log-normality of this distribution.

of knowledge on the economy-wide total factor productivity, we introduce them explicitly in the full model in Section 5. Finally, we give the definition of the general equilibrium of the model in Appendix D.1.

4 Equilibrium Research and the Market for Education

In this section, we highlight the equilibrium interdependencies between university R&D expenditure and the market for higher education. The results provide intuition for the results of our counterfactual simulations. We offer a simple version of the model without peer-effects in Appendix D.3. Proofs and additional properties can be found in Appendix D and F.

4.1 Market Structure of the Higher Education Sector

The model's equilibrium features an endogenous hierarchy of colleges which differ in their education quality. Students are stratified across institutions by ability and family income, with the highest ability and wealthiest students sorting predominantly into the highest quality colleges. This stratification is the result of optimal household decisions taking the tuition schedule as given. In turn, the tuition schedule is determined in equilibrium by household choices and the admission policies chosen by colleges.

A college which decides to offer education of quality q must choose the optimal mix of inputs, in terms of expenditures and the type of students admitted, to best deliver its targeted quality q. Given that teaching expenditures and student ability are substitutable, a college trades off lower student ability for higher tuition. This trade-off is reflected in the first-order conditions of the college problem with respect to the density over student types and to expenditures. The unique tuition schedule consistent with colleges being at an interior solution is given by the following proposition.

Proposition 1. *The equilibrium tuition schedule clearing education markets is,*

$$p(q,z) = \bar{p}\, q^{\frac{1}{\epsilon_1}} z^{-\frac{\epsilon_2}{\epsilon_1}} \tag{10}$$

where $\bar{p}$, ϵ_1 and ϵ_2 are endogenous, non-negative elasticities.

$\bar{p}$ is the endogenous intercept of the tuition schedule and determined to balance the mean supply and demand of education qualities, which is discussed in more detail in appendix F.6. ϵ_1 and ϵ_2 are determined to balance the slopes of the supply and demand. Consistent with the data and existing literature, university tuition increases with quality q and pricing exhibits third-degree price discrimination by student ability. The extent to which higher ability students pay lower out-of-pocket tuition to attend institutions of a given quality q is given by the ratio ϵ_2/ϵ_1 which reflects the value of student ability relative to tuition from the perspective of colleges. Colleges value tuition not only because they fund current teaching expenditures, but also because they can be used for research expenditures.

Given the tuition schedule (10), households choose where to send their child. This is equivalent to choosing how much to spend on colleges because the tuition schedule is strictly increasing in quality. Since the elasticity of intergenerational substitution is unitary, and technologies are log-linear, households spend a constant share of their income on tuition.

Proposition 2. *Households spend a constant share, s, of their income on tuition*

$$s = \beta\alpha\epsilon_1. \tag{11}$$

Households spend more on education when they are more altruistic (β), when a quality college education brings higher returns (α), or when the supply of education quality is more elastic (ϵ_1).

Given the equilibrium tuition schedule and the optimal spending of households, one can obtain the equilibrium sorting rule, which gives the quality of school attended by each student, depending on their family background and their own ability (h, z).

Proposition 3. *The equilibrium student sorting across colleges is given by,*

$$q(h,z) = \left(\frac{swh}{\bar{p}}\right)^{\epsilon_1} z^{\epsilon_2}. \tag{12}$$

This two-dimensional sorting rule of students is fully characterized by several endogenous variables common to all households: $sw/\bar{p}$, ϵ_1 and ϵ_2. The first term, $swh/\bar{p}$, captures the real education spending of a household with parental income wh. Parameters ϵ_1 and ϵ_2 capture the elasticity of the sorting rule with respect to family income and student ability, respectively. As discussed above, they reflect the relative valuation of tuition and student ability by colleges. As colleges' valuation for tuition increases because either teaching or research expenditures become more valuable, student sorting by family background strengthens.

An important contribution of our framework is that it yields a unique equilibrium matching of students and colleges in a setting with a continuum of colleges maximizing education quality. While Cai and Heathcote (2022) point out that no equilibrium with quality maximization would exist in a setting where all colleges are *ex ante* the same because they all would like to be at the top, colleges in our model are ordered by an endogenous knowledge hierarchy. In that sense, we relate to Epple, Romano, and Sieg (2006) who have quality maximization and an exogenous endowment hierarchy with a finite set of universities having market power. Our uniqueness result complements these earlier papers and is obtained within the class of equilibria with log-linear tuition schedules.

4.2 University R&D and the Research Share

University research is funded through tuition revenue derived from teaching activities (recall the university budget constraint in equation 9). This form of funding corresponds to the internally-funded university R&D in the data (see Figure 1). Proposition 4 characterizes the share of revenues that universities allocate to research e_R in equilibrium. We refer to it simply as the research share. Importantly, the research share depends on the equilibrium on the market for higher education. More specifically, it depends on the *dispersion* in tuition and student ability on the one hand and on the dispersion of universities' intangible capital on the other.

Proposition 4. *The research share is given by*

$$s_R = \frac{\beta\gamma_e(\Sigma_q/\Sigma_k)}{(1-\beta)\omega_e + \beta\gamma_e(\Sigma_q/\Sigma_k)} \tag{13}$$

where Σ_x *is the standard deviation of* $\ln x$ *and*

$$\frac{\Sigma_q}{\Sigma_k} = \omega_k + \omega_e\frac{\Sigma_R}{\Sigma_k} + \omega_z\frac{\Sigma_{\bar{z}}}{\Sigma_k} \tag{14}$$

where $R \equiv \mathbb{E}_{\phi(\cdot)}\left[p(q,z)\right]$ *is the average net tuition a university receives from the students it admits.*

Equation (13) shows that university spending on research is increasing in the steepness of the college quality-ladder, measured by Σ_q/Σ_k. The ratio is a sufficient statistic for the university's endogenous incentives to invest in research. It summarizes the extent to which a university with more intangible capital k can deliver a better education quality q. Indeed, given the log-normality of the model, it corresponds to the equilibrium cross-sectional elasticity of q with respect to k.[21]

To better understand the forces which determine the steepness of the college quality-ladder, equation (14) shows how Σ_q/Σ_k can be further decomposed into three components. The first, ω_k, captures the direct contribution of research to teaching quality in the education technology (5). The other two terms capture incentives which flow from university competition for tuition and talented students. They represent the fact that leading research universities attract better students, an effect summarized by $\omega_z \times \Sigma_{\bar{z}}/\Sigma_k$,

[21]The term Σ_q/Σ_k measures the percent increase in education quality resulting from an investment in R&D that increases university intangible capital by 1%.

and can charge higher tuition, captured by $\omega_e \times \Sigma_R/\Sigma_k$, both of which further improve education quality.

An important implication of equation (14) is that the relationship between education quality and university research capital is more than a feature of the education technology (ω_k); it also depends on how students endogenously sort across schools by ability and family background. When students are highly stratified in the higher education market, university incentives to spend on research may be much larger than what is implied by the direct contribution of research to teaching quality alone.

The model can rationalize university R&D even as the direct contribution of research to teaching quality becomes vanishingly small (e.g. $\omega_k \to 0$). This corresponds to a situation where intangible knowledge acts as a pure signal of the university's reputation and as a coordination device for high ability and wealthy students to congregate at the same colleges. Research in this case is purely driven by the competition for tuition and talented students.[22]

Another important implication of equation (14) is that the strength of the incentive to spend on research depends inversely on the dispersion of intangible capital across colleges. Intuitively, when institutions are highly unequal in their intangible capital, top schools face weaker incentives to further enhance their position while lower-ranked institutions find it too costly to invest in improving their rank. As a result, all types of universities invest less in research.

Equation (14) also helps understand how our calibration strategy quantifies the empirical importance of these incentives on university research. While a university's knowledge capital k may be difficult to directly measure, the model allows us to link the sufficient statistic Σ_q/Σ_k to other characteristics of the university which are observable. From the research technology in equation (6), a university's intangible capital will be closely related to

[22] In the extreme situation where $\omega_k = 0$, there are multiple equilibria in the market for higher education. But arguably the most robust and realistic equilibrium is one in which colleges with better research are also those with higher tuition and higher-quality students.

its research spending. The component $\Sigma_{\bar{z}}/\Sigma_k$ in equation (14) is therefore closely associated with the cross-sectional elasticity of student ability with respect to university research, displayed in Figure 3. Similarly, the term Σ_R/Σ_k is proportional to the cross-sectional elasticity of tuition with respect to research expenditure displayed in Figure 4.[23]

5 A Quantitative Model with Government Policies

A novel implication of the model is that university research and teaching are co-determined in equilibrium. To understand the importance of these interdependencies, we now assess how this paper's mechanism shapes the impact of federal research and tuition policies on research expenditures and knowledge production. We first introduce a number of additional quantitative extensions, which we describe in more details in Appendix E.

5.1 Quantitative Extensions

We generalize the university's research and teaching technologies to account for the contribution of faculty $(\bar{h}_T, \bar{h}_R)$ besides equipments (e_T, e_T). The university teaching technology (5) becomes $q = k^{\omega_k} \bar{z}^{\omega_z} e_T^{\omega_e} \bar{h}_T^{\omega_h}$ and the research technology (6) becomes $k' = k^{\gamma_k} e_R^{\gamma_e} \bar{h}_R^{\gamma_h}$. Following the literature on academic research, we allow for productivity spillovers of research on the real sector. We model these spillovers by assuming aggregate productivity is a function of the stock of knowledge created by the higher education sector, so that $A = \bar{A} K^{\iota_k}$ where $K = \mathbb{E}[k]$.

We also account for the intergenerational persistence of ability. Following Capelle and Matsuda (2025), we model z as the result of an intergenerational process given by $z = \xi h^{\varphi}$ where $\ln \xi \sim$ i.i.d.$\mathcal{N}(-\sigma_z^2/2, \sigma_z^2)$ is a random birth shock and φ captures the intergenerational transmission of skill from

[23] While Proposition 4 characterizes the college quality-ladder determining university research as a function of endogenous objects, Proposition 5 in Appendix D.2 expresses it in terms of the model's state variables: the dispersion of z, h and k.

parent to child. We also incorporate different time discount factors for the households and the colleges, denoted as β and β_c respectively.

Finally, we allow for a full life-cycle dynamic: each period corresponds to 4 years and individual lifecycles evolve deterministically. Each person lives for five periods as a child, then attends college for one period, and finally works as an adult for ten periods. Each household has one child midway through their adult life and sends them to college before retiring when their children enter the labor market. Across these periods households can borrow and save at exogenous interest rate r to smooth consumption during their lifetime. The household's time preference is denoted by δ.

5.2 Government Policies

The government implements two types of policies in the higher education sector: need-based student financial aid and merit-based research grants. Government policies are funded by progressive income taxes, as in Heathcote, Storesletten, and Violante (2017), with excess revenues rebated to households through a linear non-distortive consumption rebate.[24]

Federal tuition policies consist of need-based financial aid. We augment the household budget constraint (3) so that the out-of-pocket college expense for a household with income y is given by $\psi(y) \times p(q, z)$, where government subsidy covers a fraction $1 - \psi(y)$ of tuition. While such aid is, in practice, distributed through a variety of instruments, we follow the parsimonious approach of Benabou (2002) using the two-parameter policy schedule $\psi(y) = \frac{y^{\tau_n}}{1+a_n}$ where τ_n is the rate of progressivity of the need-based subsidy and $1 + a_n$ is the intercept determining the overall level of support.

Similarly, while government subsidization of university research is administered through several different programs and agencies, including the National Institute of Health, the Department of Defense, NASA, the National Science Foundation, and others, we specify a reduced-form allocation rule

[24] Specifically, $\{a_y, \tau_y\}$ parameterizes the tax-system such that after-tax income is $(1 - a_y) \times (wh)^{1-\tau_y}$.

$G(k) = \bar{G}k^{-\tau_G}$ where $\bar{G}$ and τ_G capture the average subsidy and its distribution across universities. Intuitively, government grants cover a fraction $1 - G(k)$ of a university's research (but not teaching) expenditures. The dependence of research subsidies on k reflects the meritocratic nature of government grant making and allows us to match the distribution of federal research funds observed in Figure B6.

5.3 Efficiency of the Decentralized Equilibrium

There are two sources of inefficiency in the decentralized equilibrium.[25] First the borrowing constraint prevents the efficient allocation of students across colleges, as in Capelle and Matsuda (2025). While the social planner would like to sort students according to their ability and send the best ones to the best colleges, the sorting in the decentralized equilibrium is inefficient because students are limited by their parent's capacity to pay for tuition.[26]

Second, the knowledge developed by universities has positive spillovers to the real economy. Because colleges don't internalize them, they underinvest in research and not enough knowledge is produced in equilibrium. However, this inefficiency is to some extent offset by the fact that quality-maximizing colleges face additional incentives to conduct research. As shown in section 4.2, these depend on the degree to which the higher education system is stratified. There is no reason why in equilibrium these incentives should exactly align with the spillovers to the real economy. As a result, there may be under- or over-investment in research depending on the strength of these incentives relative to that of the spillovers.[27]

[25] While this paper looks at the effects of existing policies, future research should look at their optimal design.

[26] Cai and Heathcote (2022) obtain an efficient allocation because they don't specify a borrowing constraint, not because they assume that colleges are maximizing profits.

[27] The allocation of resources under quality maximization differs from that under profit maximization. The presence of inefficiencies, however, depends on the definition of social welfare. If the social welfare function excludes the utility that colleges derive from quality, then quality maximization introduces an additional source of inefficiency. Conversely, if the social welfare function accounts for colleges' utilities, the optimality of the equilibrium allocation remains ambiguous.

Table 2: Externally Calibrated Parameters

Parameter	Description	Value	Source
δ	Time discount factor	0.85	Standard (annually 0.96)
γ_k	Research Productivity Spillover	0.52	Hall et al. (2010)
ι_k	Output Productivity Spillover	0.10	Hall et al. (2010)
τ_y	Income Tax Progressivity	0.15	Heathcote et al. (2017)
τ_n	Tuition Subsidy Progressivity	0.18	Capelle et al. (2025)
$\bar{a}_y$	Avg. household income tax	0.20	CBO
$\bar{a}_n$	Avg. student education subsidy	0.53	OECD

5.4 Calibration

Our calibration draws on the same administrative microdata sources that were used in section 2. Additional data on students' ability and parental earnings is taken from the National Longitudinal Survey of Youth 1997 (NLSY97). Data on government tuition subsidies come from the National Postsecondary Student Aid Study (NPSAS). Aggregate statistics on income inequality and aggregate household spending on education are from the Congressional Budget Office (CBO) and the OECD's *Education at a Glance*. Appendix A provides details on the sample and sources.

Externally Calibrated Parameters. The externally calibrated parameters are listed in Table 2. The time discount factor, δ, is calibrated to a 0.96 annual rate, a standard value used in the literature. We calibrate the strength of spillovers from university research, ι_k, and the persistence of intangible capital, γ_k, to match estimates in the literature reviewed by Hall, Mairesse, and Mohnen (2010). Specifically, we set $\iota_k = 0.1$, consistent with the median estimate in the literature. Similarly, we calibrate the persistence of university knowledge to generate a 15% annual depreciation rate, consistent with the literature, adjusted to a four-year frequency so that $\gamma_k = (1 - 0.15)^4 \simeq 0.52$.

To calibrate the progressivity of income taxes τ_y, we take estimates from Heathcote, Storesletten, and Violante (2017) derived from the Current Population Census (CPS) data and the NBER's TAXSIM program. Consistent with estimates from the CBO, we set the average income tax rate to 20%.[28] To calibrate the government's tuition subsidy schedule, we take estimates from Capelle and Matsuda (2025) derived from micro data from NPSAS on student financial assistance, tuition, and parental incomes. Specifically, they estimate the student-aid progressivity parameter τ_n using the regression,

$$\log(\text{net tuition}) = \tau_n \cdot \log(\text{household income}) + \mathbf{X}'\boldsymbol{\beta} + \epsilon \tag{15}$$

where $\mathbf{X}$ includes the log of ACT scores and a constant. We set the level of the subsidy schedule, $\bar{a}_n$, to match the average public subsidy to higher education. From the OECD's Education at a Glance (2020), total, private and public spending in higher education amounts to 2.6%, 1.7% and 0.9% of GDP respectively. We obtain $\bar{a}_n = 2.6/1.7 - 1 = 0.53$.

Internally Calibrated Parameters. The model's remaining parameters are jointly calibrated to internally match equilibrium characteristics of the household sector and of the market for higher education. Table 3 reports the calibrated values and Table 4 summarizes how well the model fits the data. Although no moment uniquely identifies individual parameters, we provide intuition for which moments are most informative for each parameter.

The four parameters governing the process of human capital accumulation, the degree of heterogeneity in ability, and extent of intergenerational altruism are most closely related with the four household sector data targets. The intergenerational altruism parameter β is closely associated with the share of household income spent on tuition, as can be seen in equation (11). To discipline the parameters governing the intergenerational transmission of ability (σ_z, φ), we use the NLSY97 micro data and regress children's ASVAB score on their parents earnings.[29] The slope coefficient of the regression

[28]By targeting $\bar{a}_y$ ($\bar{a}_n$) which is the average tax rate (see Appendix F for a formal definition), we can recover the values of a_y (a_n).

[29]The Armed Services Vocational Aptitude Battery (ASVAB) consists of a battery of ten

Table 3: Internally Calibrated Parameters

Parameter	Description	Value
β	Inter-generational household preference	0.20
σ_z	Children ability shock	0.74
α	Elasticity of human capital w.r.t. college quality	0.15
φ	Elasticity children ability w.r.t. parents' human capital	0.28
β_c	College time preference	0.10
ω_z	Elasticity of school quality w.r.t peer effects	0.51
ω_k	Elasticity of school quality w.r.t knowledge	0.25
ω_e	Elasticity of school quality w.r.t equipment	0.09
γ_e	Elasticity of knowledge w.r.t equipment	0.26
(a_G,τ_G)	External research grant award schedule	(0.02, 0.85)

Notes: *Additional details are contained in appendix A.*

is closely related to the elasticity of intergenerational transmission of human capital, φ, while the share of total variance explained by variation in parental income, the R^2, is inversely related to the standard error of the ability shock, σ_z. Finally the intergenerational elasticity (IGE) is informative about α, which connects the quality of education to future income.

The remaining set of parameters govern the technologies used by the higher education sector and the research grants award schedule. The elasticities of school quality and research output with respect to its inputs (e.g. ω_e, γ_e for equipment, ω_h, γ_h for faculty human capital) govern the share of revenues spent on each input. Two of these four parameters are therefore identified by the equipment expenditure share in teaching and in research. Imposing constant returns to scale on the university's education technology (e.g. $\omega_k + \omega_z + \omega_e + \omega_h = 1$), we can identify ω_h and ω_e separately for a given value of $\omega_k + \omega_z$. Similarly, with constant returns in the research technology (e.g. $\gamma_k + \gamma_e + \gamma_h = 1$), we can identify γ_h and γ_e separately given a value of γ_k.

We use the share of total research spending in total university expenditure

tests that measure knowledge and skill in several areas from maths to sentence comprehension.

Table 4: Jointly Fit Data Targets for Internal Calibration

Description	Source	Data	Model
Households Sector			
Reg. test-scores on parent's earning (slope)	NLSY	0.12	0.12
Reg. test-scores on parent's earning (R^2)	NLSY	0.11	0.11
Share of household income spent on tuition	OECD	1.6%	1.6%
Inter-generational elasticity (IGE)	Davis and Mazumder (2017)	0.40	0.40
Higher Education Sector			
Total research spending share in total expenditure	IPEDS & HERD	0.24	0.24
Std (log) university revenues	IPEDS	0.63	0.59
Innovation-Education Gap	Biasi and Ma (2021)	0.013	0.013
Grants share in total university revenue	IPEDS	0.17	0.17
Elasticity of tuition w.r.t. research expenditure	IPEDS	0.14	0.15
Elasticity of student ability w.r.t. research expenditure	IPEDS	0.34	0.34
Equipment expenditure share in teaching	IPEDS	0.40	0.40
Equipment expenditure share in research	IPEDS & HERD	0.54	0.54

Notes: *Additional details are contained in appendix A.*

to identify β_c. As can be seen from equation (13), the research share increases in β_c since the more forward-looking colleges are, the more they invest in research. The dispersion of university revenues and the elasticity of mean ability with regard to research expenditure identify ω_z; the higher ω_z, the more colleges subsidize student ability and the lower the dispersion in revenues per student across colleges. An increase in ω_z also leads high-ranked colleges to recruit more high ability students, increasing the cross-sectional correlation between average student ability and research expenditures.

To discipline ω_k, we use micro-estimates of the relation between frontier-focused education in universities and the earnings of its graduates. More specifically, we follow Biasi and Ma (2021) who estimate that a one unit decrease in the education-innovation gap is associated with a 0.011% increase in student income, after controlling for other college characteristics. Through the lens of our model, we interpret their measure of the innovation gap as $\log(k)$. Because the innovation gap is measureless, we normalize the point estimates by the standard deviation. In particular, the authors report that the standard deviation at the school level of the innovation gap is

0.85.[30] After normalization, we equate the marginal impact of knowledge on wages with the marginal impact of the innovation gap on wages, so that $\omega_k \alpha = .011/.85 \times \Sigma_k = .0129 \times \Sigma_k$.

Since university revenues in the model are made of tuition and government grants, the cross-sectional elasticity of tuition revenue with respect to research expenditure identifies the concentration of research grants across school (τ_G). We can retrieve the intercept of the grant schedule a_G, using the tuition share in total university revenue, which is the complement to the share of grants given the university budget constraint.

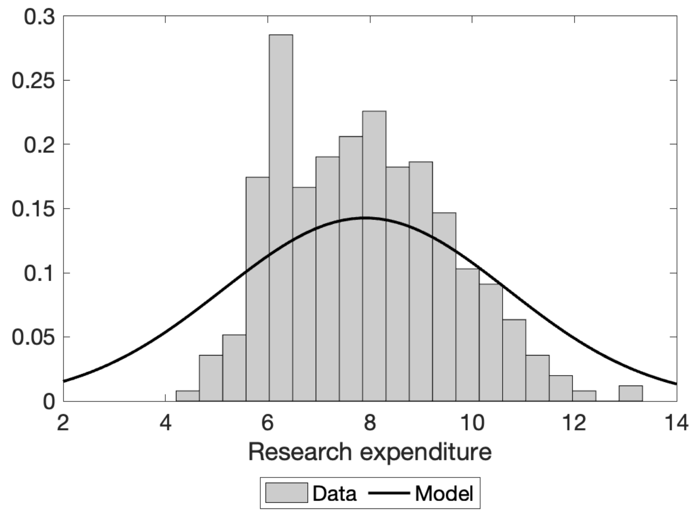
As evident from Table 4, the model performs well in matching both the aggregate and distributional characteristics of the market for higher education. In addition, the equilibrium patterns of college attendance, tuition, and research spending implied by the calibrated model, and shown in Appendix B.1, are consistent with the data. Children from wealthier families and with higher abilities tend to attend higher-quality colleges. Tuition increases with college quality and decreases with students ability. Finally, the conditional probability density functions of tuition and student ability within a college at each research expenditure level are fully consistent with the positive correlations between research spending, tuition, and student ability displayed in the empirical section.

5.5 External Validation

In this section, we review two additional tests of the model's external validity and consistency with the causal evidence reviewed above. The first validation exercise tests whether the calibrated model generates realistic variation in research expenditure, which the calibration strategy does not directly target. Figure 5 compares the variation in university R&D expenditure per student generated by the calibrated model to what is observed in the data. The figure shows that the model is mostly able to replicate the observed, but untargetted, cross-university variation in R&D expenditures,

[30] See Table 6, column 4 and section 6 in Biasi and Ma (2021).

Figure 5: The Distribution of University Research Expenditures



albeit with more mass in the tails than what is observed in the data. One potential explanation for the discrepancy in the left tail could be the fact that the National Science Board surveys do not cover universities with less than $150,000 in R&D.

The second validation exercise tests whether the calibrated model generates predictions consistent with the causal evidence from the NIH expansion presented in section 2.2. To do so, we simulate the NIH expansion within the model through an unanticipated doubling of the availability of government grants. We then conduct indirect inference on the model output by regressing the resulting change in each university's tuition on its change in research expenditure–mimicking our empirical regressions.

Comparing outcomes in the pre-intervention and post-intervention steady states, we find that each extra $1 of research expenditure yields $0.18 higher tuition in the model. Focusing on the model's transition path, we find that each extra $1 of research expenditure yields $0.11 higher tuition over the time horizon that our study examines. As a comparison, the benchmark empirical results of Table 1 imply that every extra $1 in research yields between $0.10 and $0.15 in tuition. The results show that the calibrated model does extremely well at predicting the outcome of the empirical experiments.

6 Quantitative Implications of Tuition and Research Policy

We are now ready to analyze the quantitative impact of federal tuition and research policies on research expenditures and knowledge production. The main counterfactual exercises look at how university research expenditures and educational outcomes would jointly change if we removed federal research subsidies or student financial-aid programs.

6.1 The Impact of Progressive Federal Tuition Policies

The top panel of Table 5 displays the simulation results analyzing federal tuition policies. The first row reports the effect of removing all federal tuition policies, $\{a_n, \tau_n\} = \{0, 0\}$. In historical perspective, the counterfactual corresponds to the period before the federal government substantially increased subsidies for student tuition through programs like the G.I. Bill of 1944, the Higher Education Act of 1965, and subsequent legislation. The second row reports the impact of replacing progressive federal tuition subsidies with a flat tuition subsidy (i.e. $\tau_n = 0$) whose level is chosen so that total government spending on tuition subsidies remains unchanged.

The results show that removing current need-based federal tuition policies causes university research expenditure to fall by 8.1%. Replacing the current progressive policy with a flat tuition subsidy would reduce university research spending by 2.2%–just over one quarter of the total effect. The change in university research induced by government tuition policies comes from both the overall increase in university revenue and the -0.8 percentage point change in the average university's research share.

The propositions in section 4 provide the economic intuition behind the effect of tuition policies on the research share in Table 5. By design, progressive tuition subsidies compress the dispersion in household education

Table 5: Long-Run Impact of Removing Tuition and Research Subsidies

Counterfactual	Research Spending	Human Capital	Output	Research Share	Inequality Knowledge	Inequality Human
No Tuition Subsidies	-8.1	-16.9	-17.6	-0.8	+39.2	+4.6
Flat Tuition Subsidies	-2.2	-14.8	-15.0			
No Research Subsidies	-69.1	+2.6	-8.2	+16.4	-86.6	-10.3
Flat Research Subsidies	+14.8	+9.6	+11.1			

Notes: *In percentage change relative to baseline steady state (except the research share which is reported in percentage points difference).*

expenditure by redistributing spending from wealthy households to poor households. Since lower quality schools are disproportionately attended by children from poor families, and children from rich families disproportionately enroll in high quality colleges, the compression in household education expenditure also reduces the dispersion in college revenues, Σ_R and therefore in college quality, Σ_q. The equalization of college revenues also leads to more similar research expenditures causing Σ_k to decline. However, on net the dispersion in college quality Σ_q falls by less than Σ_k, because education quality also depends on non-monetary inputs, like student ability z, whose supply does not readily change with market conditions. As a result, the college ladder Σ_q/Σ_k steepens with progressive tuition policies, leading to an increase in the intensity of university research spending, s_R. The effect highlights how tuition policies can impact university research by altering the degree of stratification in higher education.

Alongside these effects, progressive tuition subsidies also increase research by boosting the *level* of college revenues. The subsidy does so not only directly, by increasing overall tuition revenues earned by colleges, but also indirectly through the general equilibrium increase in productivity and incomes that further raises the demand for higher education. The contribution of productivity and income is evident in the 16.9% decline in human capital and 17.6% decline output following the removal of tuition subsidies.

The results show that, in addition to reducing inequality and boosting human capital accumulation, progressive tuition subsidies may also substantially increase university R&D expenditure. The rise is supported both by an increase in the level of university revenues and by an increase in the competition between universities to spend more on research. In other words, the model suggests a novel complementarity between equity and innovation in higher education: policies which promote more equitable educational outcomes also incentivize more spending on basic research.

6.2 The Impact of Meritocratic Federal Research Grants

The lower panel of Table 5 displays the simulation results analyzing federal research grant policies. The first row in this panel displays the long-run impact of removing all federal research grants, $\{a_g, \tau_g\} = \{0, 0\}$. In historical perspective, the counterfactual corresponds roughly to the period just before World War II, when the federal government rarely funded university research. The second row reports the long-run impact of adopting a flat research subsidy (i.e. $\tau_g = 0$) whose level is chosen so that total government expenditure on research grants remains unchanged.

The results show that without federal grants, university research declines by 69.1%. Importantly, the decline in university research is 6.9 percentage points *less* than the government's share of total funding for university research, which stands at 76% in the data. The gap suggests a crowding out of university research spending by government grants. In other words, universities increase internal spending on research to partially offset declines in government funds. This behavior is noteworthy in that it is at odds with the traditional view of university R&D driven only by government funding, while at the same time being consistent with data trends in recent years that suggest universities undertake just such offsetting behavior (see Figure 1).

The reason that government grants partially crowd out private spending is that their current award structure concentrates grants at top universities which already have the most resources. This increases the dispersion in university research expenditures which, in the long-run, leads to a rise in Σ_k as the gaps between institutions widen. As a result, the dispersion in college quality Σ_q increases, but by less than Σ_k because education quality also depends on the distribution of student ability z. Consequently, the college quality ladder Σ_q/Σ_k flattens, and universities have less incentive to spend on research. Quantitatively, these effects appear to be economically significant. The lower panel in Table 5 shows that the current government grant regime decreases the university research share by 16.4 percentage points. This induced decline in the research share is the main force behind the observed crowding-out effect of government research grants.

Government research grants also affect educational outcomes in higher education by altering the distribution of resources across universities. The resulting rise in the dispersion of college quality, Σ_q, leads to a modest increase in long-term income inequality Σ_h. The rise in inequality weakens the model's peer effect, leading to a 2.6% fall in human capital as colleges struggle to educate students from increasingly disparate backgrounds.

The model predicts that moving to a flat research subsidy (holding constant the aggregate amount of subsidies) would increase university research expenditure by 14.8%, increase human capital by 9.6%, and boost output by 11.1%. The flat subsidies perform better because they continue to reduce the relative cost of research expenditure without changing the market structure of the higher education sector. As a result, government grants no longer discourage internal university spending. Universities raise their internal spending on research by 16.4 percentage points, which further boosts human capital accumulation and aggregate output. By reducing the concentration of resources at top schools, the flat subsidy also results in a modest reduction of income inequality.

Taken together, the results show that federal R&D grants boost university research, but also discourage internal spending on research and exacerbate educational inequality. This is because the prevailing grant awarding system further concentrates resources at top schools. Holding constant government expenditures, moving to a flat research subsidy would boost re-

Table 6: Research Share in Robustness Checks

Robustness Exercises	Baseline	Pure Coordination Device, $\omega_k \to 0$	Teaching Expenses in Research, $\gamma_T > 0$
Level of Funding under Existing Policies	8.8	2.4	4.7
Change after Removing Tuition Subsidies	-0.8	-0.4	-0.4
Change after Removing Research Subsidies	+16.4	+10.8	+7.1

Notes: *"Level with Existing Policies" is in percentages of tuition revenues. "Changes" are in percentage points difference relative to "Levels with Existing Policies".*

search expenditure by removing distortions to the higher education sector which feed back into university research decisions. The flat research subsidy also increases output, human capital accumulation, and reduces inequality. Hence, the model suggests that flat research subsidies could be more effective, while also eliminating the trade-off between equity and innovation present in the research grant system.

6.3 Robustness: A Limiting Case of Research as a Signal ($\omega_k \to 0$)

This section contains robustness exercises examining the mechanisms behind university research and how they are calibrated. The main exercise considers how the model's predictions change in the extreme case where the direct contribution of research to teaching quality becomes vanishingly small ($\omega_k \to 0$). In this limiting case, university research only contributes to university quality indirectly by acting as a signal of school rank that attracts smarter and wealthier students. The exercise informs how sensitive the model's results are to changes in the difficult-to-measure ω_k parameter.

The second robustness exercises weakens the distinction between university research and teaching inputs by allowing some expenditures that are classified as "teaching expenses" to also enter the production of intangible capital, such that $k' = k^{\gamma_k} e_R^{\gamma_e} \bar{h}_R^{\gamma_h} e_T^{\gamma_T}$. In both robustness exercises, all model parameters are re-calibrated before recomputing the counterfactual results. More details of the robustness exercises are contained in Appendix G.

The results of the robustness exercises are displayed in Table 6. The second column shows that there is still a strong relationship between university research and teaching outcomes even when the direct contribution ω_k becomes infinitesimally small. Importantly, while the share of tuition spent on research falls from 8.8% to 2.4%, it remains strictly positive. The impact of policy falls as well, but remains substantial. The research share falls by -0.4 percentage points after the removal of tuition subsidies (rather than -0.8) and grows by 10.8 after the removal of research subsidies (rather than 16.4), representing 50% and 66% of the original policy effects, respectively.

The second robustness exercise similarly shows that the effect of research on teaching is preserved but moderated. Allowing teaching expenditures to also contribute to university intangible capital leads the research share to fall from 8.8% to 4.7%. The impact of higher education policies similarly falls. Removing tuition subsidies leads the research share to fall by -0.4 percentage points instead of -0.8, while removing research subsidies leads to an increase of 7.1 percentage points instead of 16.4.

Together, the exercises show that the model's core mechanisms are robust to alternative specifications for the university's research technology and its direct contribution to teaching outcomes. In both cases, existing tuition policies continue to boost university research while federal research subsidies crowd it out. Of course, the results also show that the particular value of these parameters, and the specification of research technologies, matter for the model's quantitative predictions and the broader contributions of university research to higher education outcomes and the real economy.

7 Conclusion

This paper develops a model in which university research depends endogenously on the market for higher education. Universities invest in research to improve their education quality and better compete for tuition and talented students. The greater the positive assortative matching of students to schools, and the more tuition rises with college rank, the stronger is the incentive for universities to spend on research.

The model can match important new features of the microdata on university research and its core mechanism is consistent with causal evidence from a natural experiment exploiting large increases in the NIH grants. The model also rationalizes why universities fund research with tuition revenue and why they continue to spend on R&D despite low returns to patenting.

The framework also has quantitatively important implications for public research and tuition policies. Calibrated exercises show that current federal need-based student financial aid programs not only reduce inequality, they also lead universities to spend more on research. Federal research grants also boost research, but partially crowds out private spending and contributes to educational inequality by concentrating resources at the top. The results suggest important new channels through which government education and innovation policies shape human capital and knowledge production at universities.

References

Akcigit, Ufuk, Douglas Hanley, and Nicolas Serrano-Velarde. 2020. "Back to Basics: Basic Research Spillovers, Innovation Policy, and Growth." *The Review of Economic Studies* 88 (1): 1–43.

Akcigit, Ufuk, Douglas Hanley, and Stefanie Stantcheva. 2022. "Optimal Taxation and RD Policies." *Econometrica* 90:645–684.

Akcigit, Ufuk, Jeremy G Pearce, and Marta Prato. 2020, September. "Tapping into Talent: Coupling Education and Innovation Policies for Economic Growth." Working paper 27862, National Bureau of Economic Research.

Arrow, Kenneth. 1962. "Economic welfare and the allocation of resources for invention." *The Economics of Science and Innovation* 1 (01): 61–77.

Azoulay, Pierre, Joshua Graff Zivin, Danielle Li, and Bhaven N. Sampat. 2019. "Public R&D Investments and Private-sector Patenting: Evidence from NIH Funding Rules." *Review of Economic Studies* 86 (1): 117–152.

Azoulay, Pierre, Joshua S. Graff Zivin, and Gustavo Manso. 2011. "Incentives and creativity: evidence from the academic life sciences." *The RAND Journal of Economics* 42 (3): 527–554.

Benabou, Roland. 2002. "Tax and Education Policy in a Heterogeneous-Agent Economy: What Levels of Redistribution Maximize Growth and Efficiency?" *Econometrica* 70 (2): 481–517 (March).

Biasi, Barbara, David J. Deming, and Petra Moser. 2020, January. In *Education and Innovation*. University of Chicago Press.

Biasi, Barbara, and Song Ma. 2021. "The Education-Innovation Gap." Working paper.

Cai, Zhifeng, and Jonathan Heathcote. 2022. "College Tuition and Income Inequality." *American Economic Review* 112 (1): 81–121 (January).

Capelle, Damien, and Kazushige Matsuda. 2025. "The Great Gatsby Goes to College: Tuition, Inequality, and Intergenerational Mobility." *Working Paper.*

Council on Government Relations. 2019, April. "Excellence in Research: The Funding Model, FA Reimbursement, and Why the System Works." Technical Report.

Davis, Jonathan, and Bhashkar Mazumder. 2017, March. "The Decline in Intergenerational Mobility After 1980." Working paper series WP-2017-5, Federal Reserve Bank of Chicago.

Duflo, Esther, Pascaline Dupas, and Michael Kremer. 2011. "Peer Effects, Teacher Incentives, and the Impact of Tracking: Evidence from a Randomized Evaluation in Kenya." *American Economic Review* 101 (5): 1739–74 (August).

Epple, Dennis, and Richard Romano. 2010. "Peer Effects in Education: A Survey of the Theory and Evidence." *Handbook of Social Economics* 1B (1): 885–928.

Epple, Dennis, Richard Romano, and Holger Sieg. 2006. "Admission, Tuition, and Financial Aid Policies in the Market for Higher Education." *Econometrica* 74 (4): 885–928.

Epple, Dennis, and Richard E. Romano. 1998. "Competition between Private and Public Schools, Vouchers, and Peer-Group Effects." *The American Economic Review* 88 (1): 33–62.

Figlio, David N., and Marianne E. Page. 2002. "School Choice and the Distributional Effects of Ability Tracking: Does Separation Increase Inequality?" *Journal of Urban Economics* 51 (3): 497–514.

Hall, Bronwyn, and Fumio Hayashi. 1989, May. "Research and Development As An Investment." Nber working papers 2973, National Bureau of Economic Research, Inc.

Hall, Bronwyn, Jacques Mairesse, and Pierre Mohnen. 2010. "Measuring the Returns to RD." Chapter 24 of , Volume 2, 1033–1082. Elsevier.

Heathcote, Jonathan, Kjetil Storesletten, and Giovanni L. Violante. 2017. "Optimal Tax Progressivity: An Analytical Framework*." *The Quarterly Journal of Economics* 132 (4): 1693–1754 (06).

Hvide, Hans K., and Benjamin F. Jones. 2018. "University Innovation and the Professor's Privilege." *American Economic Review* 108 (7): 1860–98 (July).

Jaffe, Adam B. 1989. "Real Effects of Academic Research." *The American Economic Review* 79 (5): 957–970.

Klette, Tor Jakob. 1996. "RD, Scope Economies, and Plant Performance." *The RAND Journal of Economics* 27 (3): 502–522.

Lach, Saul, and Mark Schankerman. 2008. "Incentives and invention in universities." *The RAND Journal of Economics* 39 (2): 403–433.

Merton, Robert K. 1973. *The Sociology of Science: Theoretical and Empirical Investigations*. University of Chicago Press.

Mowery, David C., Richard R. Nelson, Bhaven N. Sampat, and Arvids A. Ziedonis. 2015. *Ivory Tower and Industrial Innovation: University-Industry Technology Transfer Before and After the Bayh-Dole Act*. Stanford University Press.

National Science Board. 2018. "The State of U.S. Science and Engineering." Technical Report NSB-2018-1.

Nelson, Richard R. 1959. "The Simple Economics of Basic Scientific Research." *Journal of Political Economy* 67 (3): 297–306.

Rosenberg, Nathan. 1990. "Why Do Firms Do Basic Research (with Their Own Money)?" *Research Policy* 19 (02): 165–174.

Rosenberg, Nathan, and Richard R. Nelson. 1994. "American universities and technical advance in industry." *Research Policy* 23 (3): 323–348.

Rothaermel, Frank T., Shanti D. Agung, and Lin Jiang. 2007. "University entrepreneurship: a taxonomy of the literature." *Industrial and Corporate Change* 16 (4): 691–791 (07).

Sacerdote, Bruce. 2014. "Experimental and Quasi-Experimental Analysis of Peer Effects: Two Steps Forward?" *Annual Review of Economics* 6 (1): 253–272.

Smith, Pamela W. 2006, October. "The National Institutes of Health (NIH): Organization, Funding, and Congressional Issues." Nber working papers ADA458502, Library of Congress.

Stephan, Paula E. 1996. "The Economics of Science." *Journal of Economic Literature* 34 (3): 1199–1235.

Online Appendix

University Research and the Market for Higher Education

Titan Alon, Damien Capelle and Kazushige Matsuda

A Data Sources

A.1 Main Sample and Data Sources

Our primary sample includes all 4-year public and private non-profit institutions in the United States. Data primarily comes from the National Center for Education Statistics Integrated Postsecondary Education Data System (IPEDS) which provides university level microdata for the universe of domestically accredited higher-education institutions. We merge in additional data from the National Science Foundation's Higher Education Research and Development Survey (HERD) on research spending by field and source of funds, the Association of University Technology Managers (AUTM) Patent Licensing Survey, and Web of Science (WoS) bibliometric data from the CWTS Leiden Rankings. The paragraphs below provide notes for each data figure in the paper. The sections that follow provide further details on each of the main data sources.

Figure 1. The figure reports total university research expenditures by source of funds in 2012 U.S. dollars. Government sources include research grants and contracts. Non-profit funding is included in the Other category. Underlying data are from the Higher Education Research and Development (HERD) survey, 1972-2018.

Figure 2. The figure reports the distribution of gross licensing revenue divided by total research expenditure. The underlying data source is the AUTM Licensing Activity Survey, and the sample includes all responding US universities from 1991-2018. Licensing revenue includes cumulative reported gross license income and research expenditure reports cumulative

non-federal, non-industrial institutional research spending. All values are converted to cumulative real 2015 dollars using the GDP price deflator.

Figure 3. SAT scores are the sum of math and verbal scores calculated as the average of the university's reported 25^{th} and 75^{th} percentiles. Data comes from the Integrated Postsecondary Education Data System with points representing university level averages for 2012-2015.

Figure 4. Tuition is the average tuition revenue the university receives per full-time equivalent student, net of any university discounts or allowances. research expenditure is total university spending for activities specifically organized to produce research outcomes, including by institutes, research centers, and individuals. Data retrieved the Integrated Postsecondary education Data System (IPEDS). Points are 2012-2015 university averages in log-scale.

Figure 5. This figure plots a histogram of the (log) in sample empirical distribution of university R&D expenditure per student. The solid line is the calibrated model's (non-targeted) prediction of the distribution of university R&D expenditure. Underlying data come from the NCES IPEDS.

A.2 Integrated Postsecondary Education Data System (IPEDS)

The Integrated Postsecondary Education Data System is managed by the National Center for Education Statistics and brings together interrelated annual surveys. The completion of all IPEDS surveys is required by law for any institution participating in federal student financial aid programs (such as Pell grants or federal student loans). The data system provides a wealth of university level longitudinal data on institutional characteristics, prices, admissions, enrollment, student financial aid, degrees conferred, and detailed revenue and expenditure summaries.

The main variables we take from IPEDS are university research expenditure, tuition, government grants, student SAT scores, faculty salaries.

A.3 Higher Education Research and Development Survey (HERD)

The Higher Education Research and Development Survey (HERD) is administered by the National Science Foundation and gathers information on research expenditures at U.S. colleges and universities. The survey provides detailed breakdowns of university level research spending by type, source, and field as well as auxiliary institutional details. It is an annual census of all higher education institutions which separately accounted for at least $150,000 in research expenditure in the fiscal year. Before 2010, it includes only institutions with degree programs in science and engineering (S&E).

We use the HERD survey primarily to disaggregate university research by source (i.e. government, internal, business) and by the type of expenditure (i.e. equipment or salaries). We also use HERD to construct the instruments for our NIH regressions. In particular, we take microdata on university RD spending by source and field to calculate the university share of federal life science funding before the policy change.

A.4 Association of University Technology Managers Patent Licensing Survey

The Association of University Technology Managers (AUTM) grew out of the Society of University Patent Administrators (SUPA) and is focused on developing and disseminating best practices for university technology transfer offices (TTO). Its annual Licensing Activity Survey has run for over twenty years and gathers self-reported data from member institutions on research funding, the impact of innovation, patenting activity, licensing activity, the number of campus start-ups, and other innovation related metrics.

We use the AUTM Licensing survey primarily for information on university patenting and the gross licensing revenue it takes in.

A.5 CWTS Leiden Rankings Bibliometric Micro Data

The Leiden Rankings are produced by the Center for Science and Technologies Studies (CWTS) at Leiden University. The rankings are based on bibliometric publication and citation data in the Web of Science (WoS) database produced by Clarivate Analytics. The data are processed with sophisticated bibliometric techniques to ensure comparable and consist of only high quality international scientific journals that are amenable to citation analysis.

We use the bibliometric micro data underlying the Leiden Rankings to measure university publications and citations.

A.6 National Postsecondary Student Aid Study (NPSAS)

The National Postsecondary Student Aid Study, conducted by the NCES, is a nationally representative cross-sectional survey of undergraduate and graduate students enrolled in postsecondary education. It provides individual level characteristics of postsecondary students with a special focus on how they finance their education.

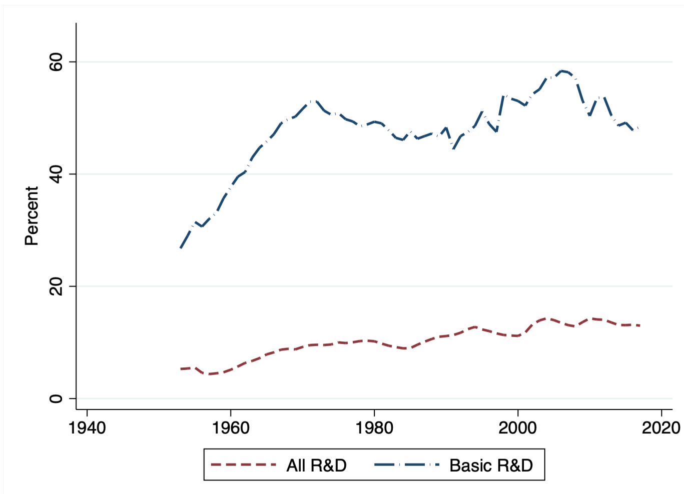
We use the NPSAS to gather individual level data on tuition, education subsidies, and family income. We use these variables to estimate a reduced form schedule for higher education subsidies.

A.7 National Longitudinal Survey of Youth (NLSY)

The NLSY is a nationally representative longitudinal survey managed by the U.S. Bureau of Labor Statistics that follows a cohort of American youth born between 1980-1984. Respondents are between the ages of 12-17 when they first enter the interview rotation in 1997. The survey collects data on labor market activity, schooling, fertility, program participation, health, family background, beliefs, and much more. We draw on the NLSY 1997 for data on student test scores and family background which informs parameters governing inter-generational dynamics.

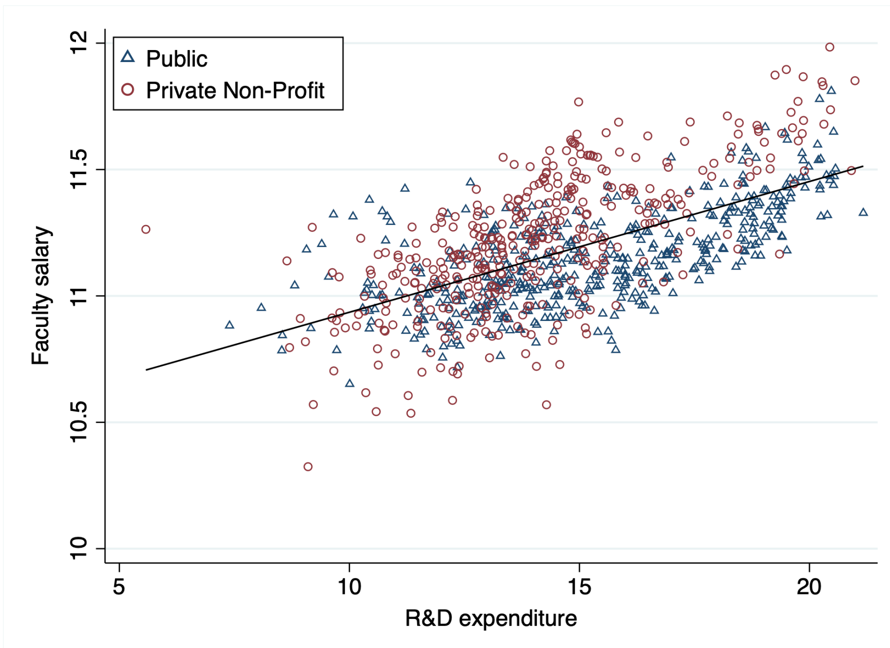
B Additional Figures

Figure B1: Higher education research expenditure as share of national total



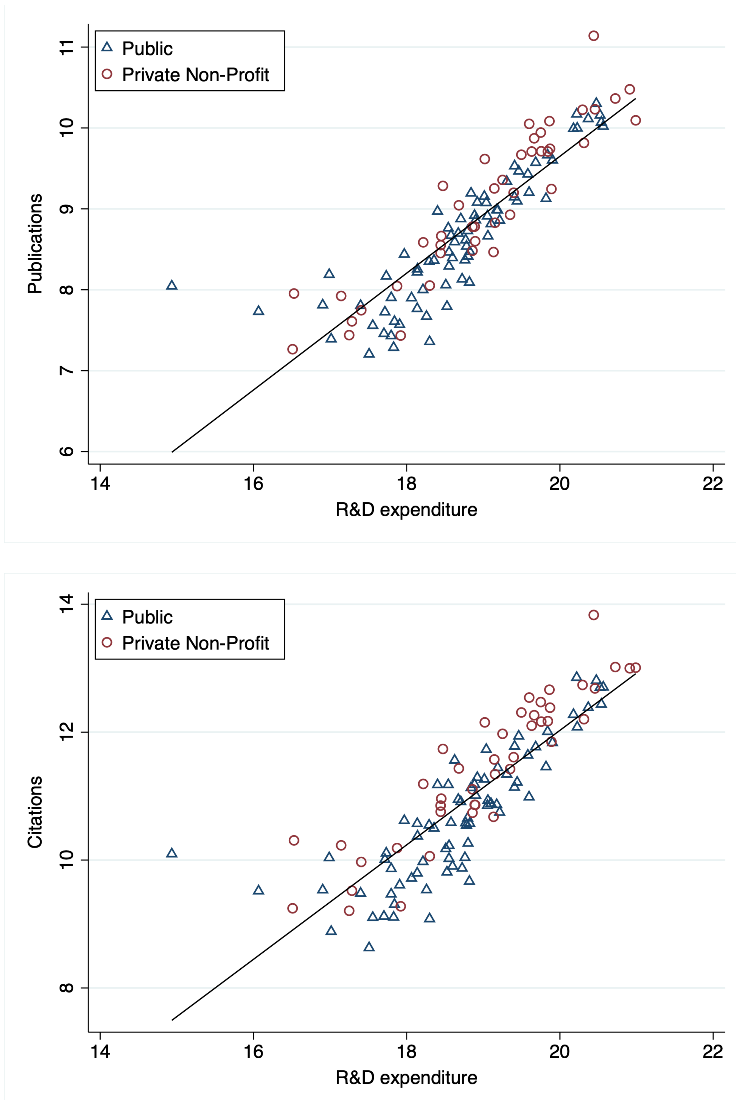
Notes: *Y-axis represents the higher education sector's share of total domestic research and development expenditures, by type. Underlying data come from National Science Board (2018).*

Figure B2: University Research Spending and Faculty Compensation



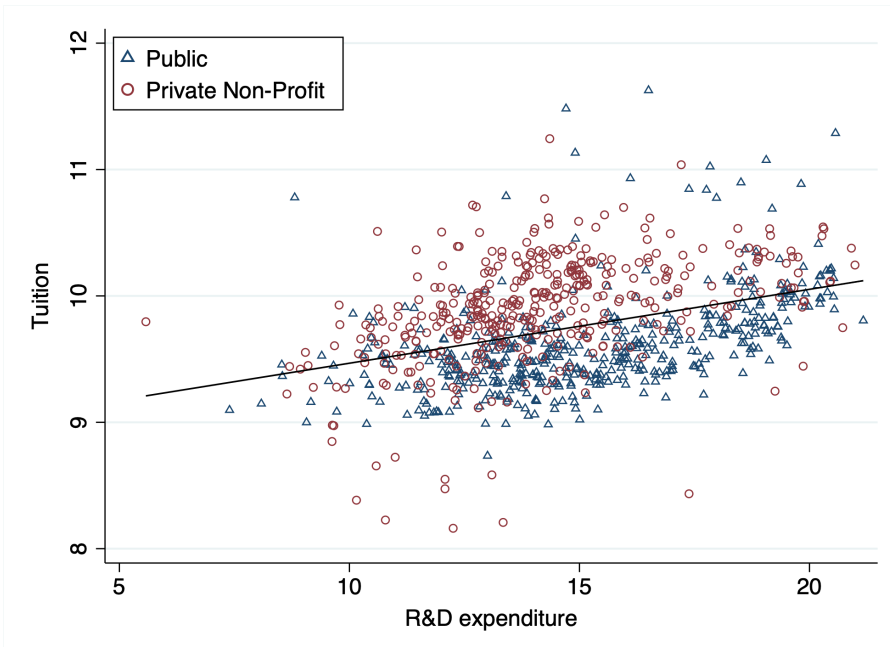
Note: *Faculty salary is the average salary for full-time faculty members on 9-month equated contracts. Research expenditure is total university spending for activities specifically organized to produce research outcomes, including by institutes, research centers, and individuals. Data comes from the Integrated Postsecondary Education Data System with points representing university level averages for 2012-2015.*

Figure B3: University Research Spending and Knowledge Creation



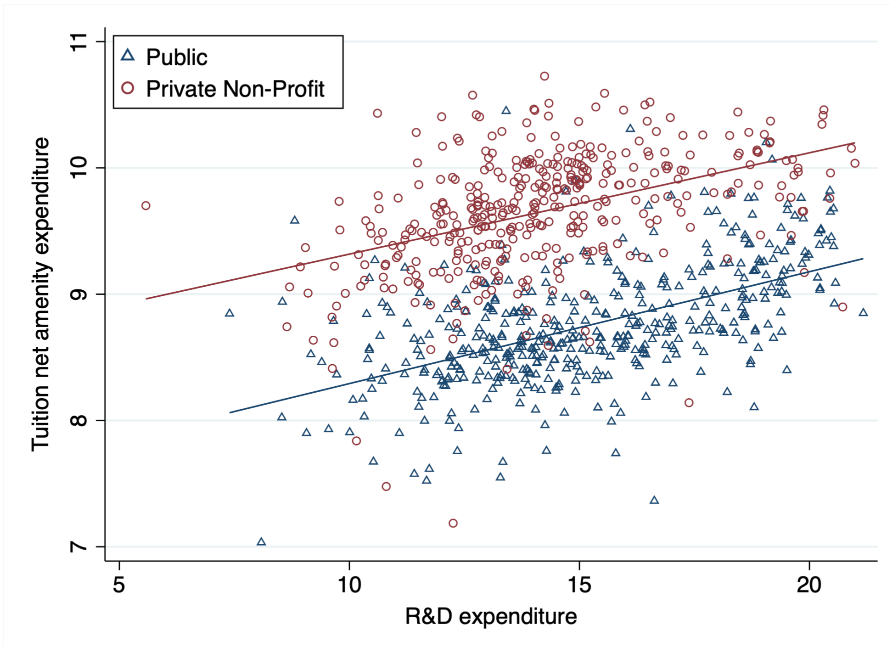
Note: *Publication and citation data come from the CWTS Leiden Ranking derived from the core collection of the Web of Science (WoS) for the years 2015-2018. research expenditure is total university spending for activities specifically organized to produce research outcomes, including by institutes, research centers, and individuals. Research expenditure data come from IPEDS with points representing university averages for 2012-2015.*

Figure B4: University research spending and tuition with state and local appropriations



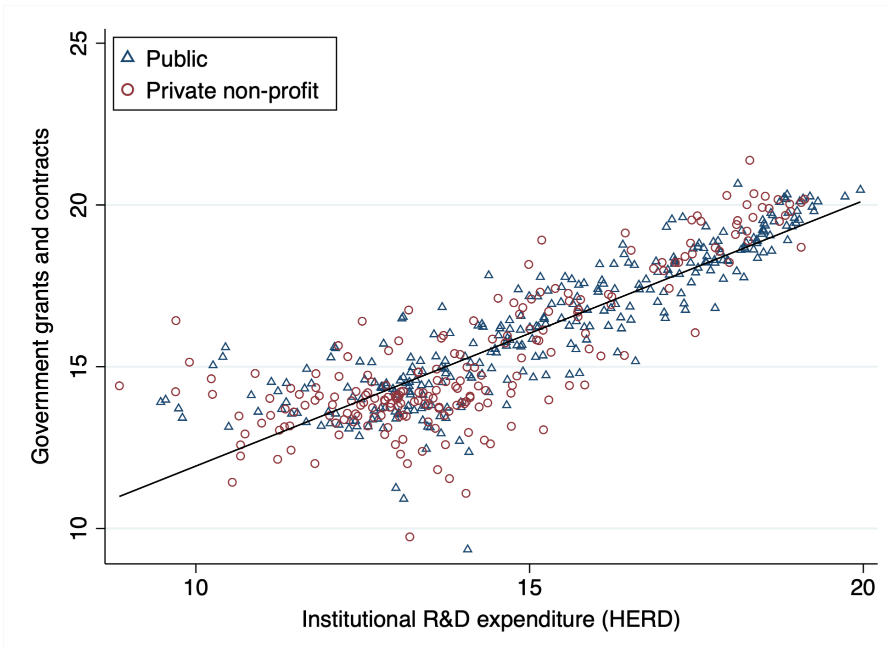
Notes: *Tuition is the average tuition revenue the university receives per full-time equivalent student, net of any university discounts or allowances, but including state and local appropriations per capita. Research expenditure is total university spending for activities specifically organized to produce research outcomes, including by institutes, research centers, and individuals. Data retrieved the Integrated Postsecondary education Data System (IPEDS). Points represent (log) university level averages from 2012-2015.*

Figure B5: University R&D spending and tuition net of student services expenditures, by sector



Notes: *Tuition is the average tuition revenue the university receives per full-time equivalent student, net of any university discounts or allowances, and net of expenditures on student services per capita. Student services includes spending on activities whose primary purpose is to contribute to students emotional and physical well-being and to their intellectual, cultural, and social development outside the context of the formal instructional program. Registrar and admissions expenses are also included. research expenditure is total university spending for activities specifically organized to produce research outcomes, including by institutes, research centers, and individuals. Data retrieved the Integrated Postsecondary education Data System (IPEDS). Points represent (log) university level averages from 2012-2015.*

Figure B6: University Research Spending and Government Grants



Notes: *Institutional research expenditures correspond to internal university funds that are separately budgeted for individual research projects. Government grants and contracts include funds received from the federal, state, or local government for research, training, or other public service. Points correspond to 2012-2015 university averages in log-scale. Data on institutional research is from the Higher Education Research and Development Survey (HERD). Data on grants and contracts is from the Integrated Postsecondary Education Data System (IPEDS).*

B.1 Model Implications

Figure B7: Quality attended and tuition paid in equilibrium by family income and child ability

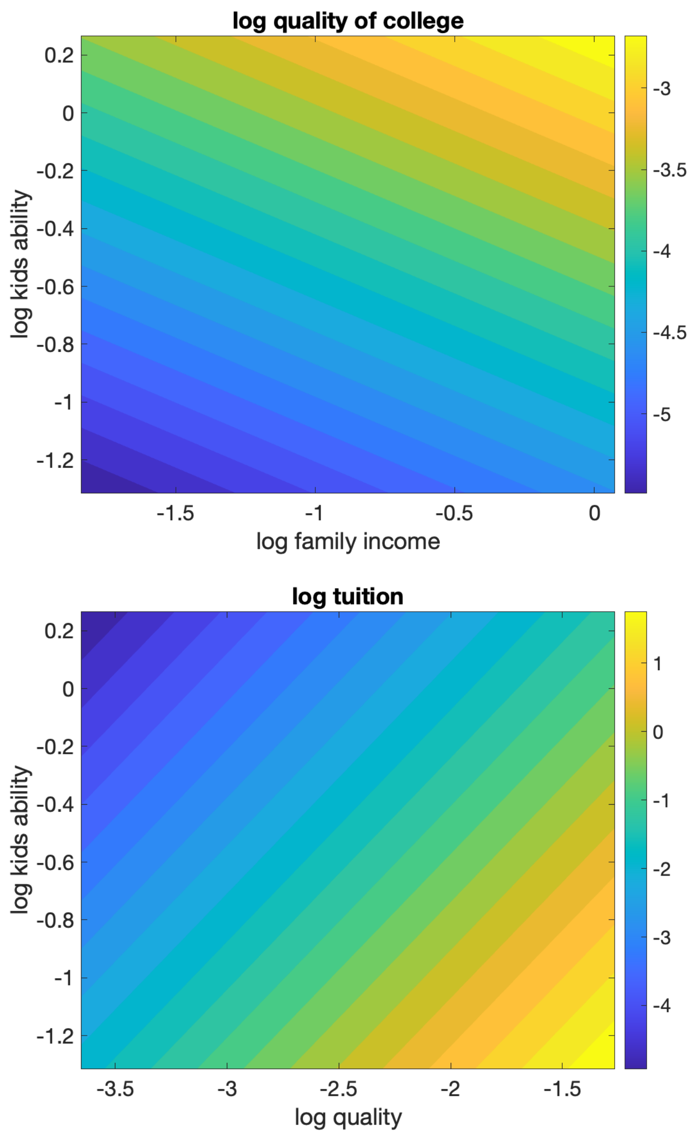
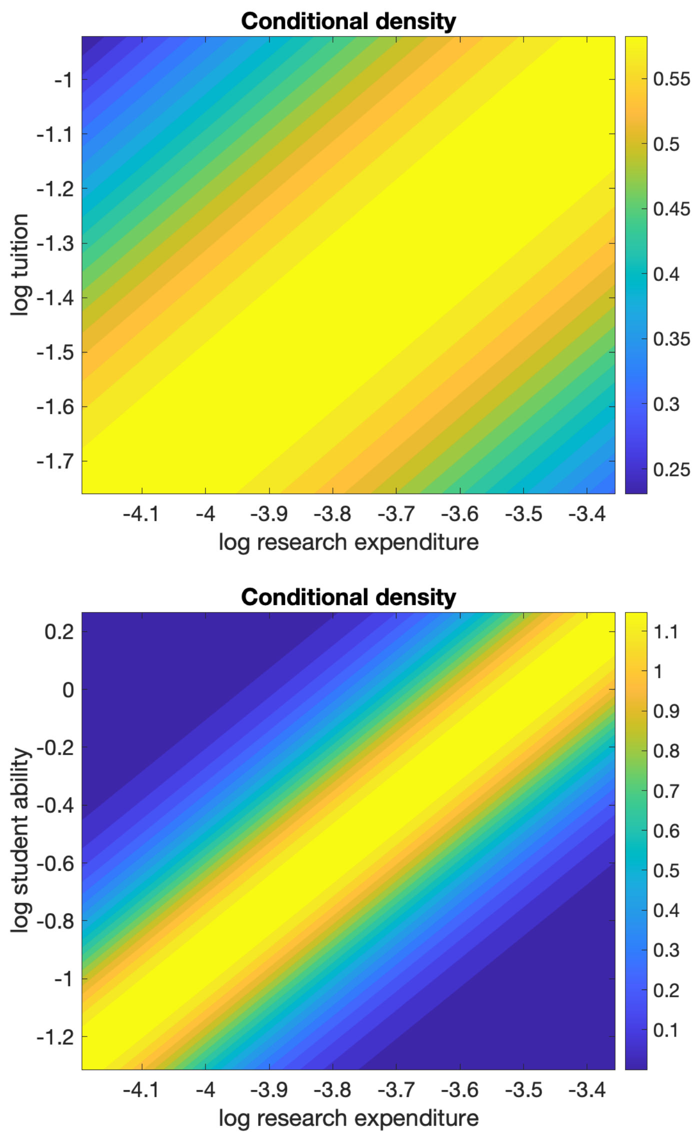


Figure B8: Within-college density of tuition paid and student ability (colleges ranked by their per-student research expenditure)



C Additional Tables

Table C1: Characteristics of top 25 research universities, by total research spending

Institution	Total research	Type of research			Source of research funding					
	(millions USD)	Fundamental	Applied	Development	Federal Gov	State Gov	Intsitutional	Business	Nonprofit	Other
Johns Hopkins University	2206	64%	27%	9%	87%	0%	4%	2%	6%	0%
University of Michigan-Ann Arbor	1354	59%	40%	1%	57%	0%	34%	4%	4%	1%
University of Washington-Seattle Campus	1165	65%	23%	12%	78%	2%	6%	3%	8%	2%
University of Wisconsin-Madison	1118	93%	6%	1%	50%	7%	33%	2%	7%	2%
University of California-San Diego	1080	80%	6%	13%	58%	4%	14%	7%	9%	8%
University of California-San Francisco	1072	86%	0%	14%	51%	4%	18%	6%	12%	9%
Duke University	1019	37%	16%	47%	56%	0%	13%	22%	7%	2%
University of California-Los Angeles	985	65%	24%	11%	51%	4%	19%	5%	14%	7%
Stanford University	958	63%	27%	10%	68%	4%	10%	8%	9%	1%
University of North Carolina at Chapel Hill	954	63%	27%	10%	64%	2%	23%	3%	7%	1%
Harvard University	940	70%	26%	4%	61%	0%	21%	4%	11%	2%
Massachusetts Institute of Technology	891	63%	29%	9%	55%	0%	10%	15%	11%	10%
Columbia University in the City of New York	884	67%	25%	8%	70%	2%	13%	4%	9%	3%
Cornell University	871	35%	49%	17%	52%	8%	22%	4%	11%	3%
University of Pittsburgh-Pittsburgh Campus	864	64%	27%	9%	68%	1%	17%	2%	4%	8%
University of Minnesota-Twin Cities	861	67%	29%	4%	57%	6%	29%	3%	2%	4%
University of Pennsylvania	842	92%	1%	7%	75%	2%	7%	8%	7%	0%
Texas A & M University-College Station	809	78%	20%	2%	37%	20%	28%	8%	6%	2%
Pennsylvania State University-Main Campus	807	28%	50%	23%	66%	6%	19%	4%	5%	0%
Yale University	755	94%	4%	2%	66%	1%	21%	4%	7%	1%
University of California-Berkeley	748	91%	9%	0%	44%	7%	21%	11%	12%	5%
Georgia Institute of Technology-Main Campus	728	63%	22%	15%	71%	2%	19%	6%	1%	1%
University of California-Davis	718	66%	22%	12%	47%	8%	25%	6%	8%	6%
University of Florida	710	86%	10%	3%	41%	15%	33%	4%	5%	2%
Washington University in St Louis	688	48%	26%	26%	62%	1%	17%	7%	12%	1%

Notes: *Top 25 research universities, ranked by average annual research between 2012-2018. Research expenditures reported in millions of 2015 US dollars. Columns provide breakdown by type of research and source of funding. Underlying data is from the NSF Higher Education Research and Development (HERD) survey.*

D Additional Model Properties

D.1 Definition of Market Clearing and Equilibrium

We focus on a steady-state equilibrium in which all cross-sectional distributions are time invariant and prices are constant. An equilibrium consists of a household value function $U(h,z)$ and associated policy functions $\{c(h,z), q(h,z)\}$; the university value function $V(k)$ and associated university policy functions $\{\phi(z|k),\, e_R(k),\, e_T(k),\, q(k)\}$; and an equilibrium tuition price schedule $p(q,z)$ and measures $\mu_h(h,z)$ and $\mu_c(k)$ such that, given the tuition price schedule, $\{U(h,z), c(h,z), q(h,z)\}$ solves the household problem in (2), $\{V(k), \phi(z|k), e_R(k), e_T(k)\}$ solves the university problem in (8), and markets clear for all combinations of quality $Q \subset \mathbb{R}^+$ and student ability $Z \subset \mathbb{R}^+$ so that

$$\int \mathbb{1}\left[q(h,z) \in Q\right] \mathbb{1}\left[z \in Z\right] d\mu_h = \int \left(\int_{z \in Z} d\phi(z|k) \right) \mathbb{1}\left[q(k) \in Q\right] d\mu_c \tag{16}$$

where $q(h,z)$ is the optimal education demand of a household (h,z) and policy $q(k)$ is the optimal education quality supplied by a university of type k.

D.2 Equilibrium college quality-ladder

While Proposition 4 provides conceptual insight and helps link the model to the data, one drawback of the characterization is that most of its elements are themselves endogenous objects. To provide a more fundamental characterization of how the model works, Proposition 5 expresses the college quality-ladder determining university research in terms of the model's state variables: the dispersion of z, h and k. The alternative characterization, while adding insight, still depends on the endogenous parameters governing the market structure of the higher education system, ϵ_1 and ϵ_2, whose determination we discuss in greater detail below.

Proposition 5. *The equilibrium college quality-ladder depends on the market struc-*

ture of the higher education sector and can be expressed as

$$\frac{\Sigma_q}{\Sigma_k} = \sqrt{\epsilon_1^2 \left(\frac{\Sigma_h}{\Sigma_k}\right)^2 + \epsilon_2^2 \left(\frac{\sigma_z}{\Sigma_k}\right)^2} \tag{17}$$

The first term in equation (17) captures the dispersion in household expenditures on education and, through ϵ_1, the extent to which they accrue to colleges of different qualities. The second term measures the variation in student abilities and, through ϵ_2, the extent to high ability students congregate at high quality colleges. University research spending is higher when household education expenditures are more unequal (e.g. high Σ_h) or if there is large variation in the abilities of students (e.g. high σ_z). Conversely, it is low when colleges' intangible capital are ex-ante highly unequal (e.g. high Σ_k), since universities are farther from their competing institutions and so overtaking them in the hierarchy of colleges would require larger and more costly investments in research. Proposition 5 also shows that universities spend more on research when the elasticities of education quality to tuition revenue and ability are high (e.g. high ϵ_1 and ϵ_2).

Propositions 4 and 5 also show how the supply and demand for education shape the equilibrium quality-ladder which incentivizes university research. On the demand side, heterogeneous households (h, z) demand heterogeneous education qualities. From the sorting rule in Proposition 3, a household of type (h, z) will demand education quality $\ln q = const. + \epsilon_1 \ln h + \epsilon_2 \ln z$. Due to the log-normality of the model, we can summarize the distribution of education quality demand using the second moments. Letting Σ_q^D denote the distribution of household demand for education quality,

$$\Sigma_q^D = \sqrt{\epsilon_1^2 \Sigma_h^2 + \epsilon_2^2 \sigma_z^2}$$

Similarly, Proposition 4 shows that the distribution of education quality supplied is,

$$\Sigma_q^S = \omega_k \Sigma_k + \omega_e \Sigma_R + \omega_z \Sigma_{\bar{z}}$$

Market clearing in the higher education sector (equation (16)) requires that the distribution of education demand, Σ_q^D, equals the distribution of education supplied, Σ_q^S, so that

$$\sqrt{\epsilon_1^2 \frac{\Sigma_h^2}{\Sigma_k^2} + \epsilon_2^2 \frac{\sigma_z^2}{\Sigma_h^2}} = \omega_k + \omega_e \frac{\Sigma_R}{\Sigma_k} + \omega_z \frac{\Sigma_{\bar{z}}}{\Sigma_k}$$

which elucidates the two equivalent characterizations of the college quality-ladder in Propositions 4 and 5. The parameters ϵ_1 and ϵ_2, which shape the sorting rule and tuition schedule, are determined in equilibrium to balance supply and demand and clear education markets. More specifically, parameter ϵ_1 adjusts to clear the supply and demand for education in the above equation, while ϵ_2 is simultaneously determined by the marginal rate of substitution between student ability z and monetary inputs, given by

$$\frac{\epsilon_1}{\epsilon_2} = \frac{\omega_e + \beta(1-\beta)^{-1}\gamma_e(\Sigma_q/\Sigma_k)}{\omega_z}. \tag{18}$$

Although the solution to the model can be fully characterized analytically, ϵ_1 and ϵ_2 remain only implicitly defined since they depend on the (endogenous) steepness of the quality-ladder. The main difficulty is that the sorting of students is two-dimensional. To provide additional insight into the model's economic mechanisms, the next section considers a special case without peer effects ($\omega_z = 0$) in which the model's equilibrium can be fully characterized in terms of exogenous variables.

D.3 An Equilibrium without Peer Effects

Proposition 6 characterizes the model's equilibrium in the absence of peer effects.

Proposition 6. *When $\omega_z = 0$, there are no peer effects in education, so $\epsilon_2 = 0$ and*

$$\epsilon_1 = \omega_e + \omega_k \frac{\Sigma_k}{\Sigma_h} \tag{19}$$

where the steady state dispersion of college intangible capital is given by,

$$\Sigma_k = \frac{\gamma_e}{1 - \gamma_k} \Sigma_h \tag{20}$$

and the steady state distribution of household human capital is given by,

$$\Sigma_h^2 = \frac{\sigma_z^2}{1 - \left(\alpha \left(\omega_e + \omega_k \frac{\gamma_e}{1-\gamma_k} \right) \right)^2} \tag{21}$$

In the case without peer-effect, knowledge intangible capital and final goods are the only two inputs to produce education quality. Universities have no incentives to attract talented students and as a result there is perfect sorting across colleges based on family income ($\epsilon_2 = 0$).[31]

These expressions show important equilibrium interactions between the market for higher education and university research. For instance, consider a change in the research technology, such as a rise in γ_k or γ_e, which increases R&D expenditure and leads to an increase in the dispersion of college intangible capital Σ_k in equation (20). From equation (19), we see that the increased dispersion in college intangible capital will decrease the price elasticity of demand, leading to an increase in household education expenditures and greater stratification of students by family background in higher education. In the long-run, the increase in university research spending leads to greater inequality in educational outcomes and more earnings inequality, steepening the college quality-ladder further and reinforcing university incentives to spend on research.

[31] Plugging the results of Proposition 6 into the formulas contained in Propositions 1 through 5 provides expressions for the equilibrium tuition schedule, household education expenditure, university research spending, and the sorting rule determining the stratification of students across the college quality-ladder.

This example illustrates the role of universities as engines of human capital accumulation and innovation, but also of inequality. Equation (21) shows how the education system amplifies initial differences between students, σ_z^2, leading to larger variation in adult human capital. The equation also demonstrates how this amplification depends on the returns to education through α, differences in educational expenditures per students through ω_e, and the contribution of research through $\omega_k \frac{\gamma_e}{1-\gamma_k}$. The final term captures an important equilibrium feedback in the model whereby university research today also influences the future demand-side of the education market.

E Quantitative Extensions and Government Policies

E.1 Quantitative Extensions

Faculty in Teaching and Research. We generalize the university's research and teaching technologies to account for the contribution of faculty. Specifically, the university teaching technology (5) becomes $q = k^{\omega_k} \bar{z}^{\omega_z} e_T^{\omega_e} \bar{h}_T^{\omega_h}$ and the research technology (6) becomes $k' = k^{\gamma_k} e_R^{\gamma_e} \bar{h}_R^{\gamma_h}$, where the contribution of faculty depends on their average human capital, $\bar{h}_x = \mathbb{E}_{\mu_x(.)}[\,h\,]$, where $\mu_x(\cdot)$ is the endogenous distribution of faculty chosen by the university to perform task $x \in \{R, T\}$. Allowing the university to choose different compositions of research faculty, $\mu_R(\cdot)$, and teaching faculty, $\mu_T(\cdot)$, captures the fact that they can partially specialize these tasks internally by hiring dedicated teaching faculty or by increasing teaching loads for research faculty. The inclusion of faculty requires an additional labor market clearing condition for labor across the education, research, and production sectors.[32]

Explicitly including faculty in the university production technologies allows us to make full use of the microdata which separately reports university expenditures on faculty and equipment, both within teaching and

[32] In particular, letting H_F denote the measure of effective labor in the production sector, the labor market clearing condition is akin to $H_F + \int h\, \mu_R(h|k) d\mu_c + \int h\, \mu_T(h|k) d\mu_c = \int h\, d\mu_h$

research activities. It also allows the model to generate the sorting of faculty across the college quality-ladder, as summarized in figure B2. Moreover, since faculty are drawn from the adult population, the distribution of faculty human capital is endogenous to the model and depends on Σ_h^2.

Supply-Side Spillovers from University Research. Much of the literature on academic research emphasizes the productivity spillovers it generates for the production sector. To account for these effects, we assume that the technology to produce the final goods, which are used for consumption and as inputs in the education and research, is subject to productivity spillovers from the knowledge created by academic research. Formally, firms operate a constant returns to scale production technology $F(H_F) = A \cdot H_F$, where H_F is aggregate effective labor in the production sector and A is total factor productivity (TFP). To incorporate spillovers from academic research, we assume aggregate TFP is a function of the stock of knowledge created by the higher education sector, so that $A = \bar{A}K^{\iota_k}$ where $K = \mathbb{E}[k]$. While the productivity spillovers from academic research are not crucial for our mechanism or conclusions, they help quantitatively account for an important general equilibrium channel whereby changes in university research output can effect household demand for education through wages.

Household Demographics and Intergenerational Dynamics. We introduce a more general process to determine a child's ability at the start of college, z. Following Capelle and Matsuda (2025), we model z as the result of an intergenerational process given by,

$$z = \xi h^{\varphi} \tag{22}$$

where $\ln \xi \sim \text{i.i.d.}\mathcal{N}(-\sigma_z^2/2, \sigma_z^2)$ is a random birth shock and φ captures the intergenerational transmission of skill from parent to child. The more general process allows the model to match microdata on the intergenerational correlation in human capital that is not accounted for by education investments. In the absence of these effects, the model may overstate the productivity of financial investments in education quality. The intergenerational transmission process also increases the persistence and aggregate impact of shocks to the higher education system.

Finally, we adopt a more flexible parameterization of time preference and intergenerational benevolence. We allow households to borrow and save at exogenous interest rate r to smooth consumption during their lifetime. Each period corresponds to 4 years and individual lifecycles evolve deterministically. Each person lives for five periods as a child, then attends college for one period, and finally works as an adult for ten periods. Each household has one child midway through their adult life and sends them to college before retiring when their children enter the labor market. See appendix F for details.

These changes allows us to differentiate between a household's time preference (δ), its intergenerational benevolence (β), and the university discount factor (β_c). This allows us to calibrate the time-scale of the quantitative model (through δ) separately from the benevolence factors β and β_c, which determine the weight that households and universities assign to future generations.

E.2 Government Tuition and Research Policies

The government implements two types of policies in the higher education sector: merit-based research grants and need-based student financial aid. Government policies are funded by progressive income taxes, as in Heathcote, Storesletten, and Violante (2017), with excess revenues rebated to households through a linear non-distortive consumption rebate.[33] We take the prevailing tax schemes as given and do not consider the optimal design of government R&D taxation policies within our counterfactuals, as in Akcigit, Hanley, and Stantcheva (2022).

Tuition Policies. Federal tuition policies consist of progressive need-based financial aid. We augment the household budget constraint in (3) so that

[33]Specifically, $\{a_y, \tau_y\}$ parameterizes the tax-system such that after-tax income is $(1 - a_y) \times (wh)^{1-\tau_y}$.

the out-of-pocket college expense for a household with income y is given by $\psi(y) \times p(q, z)$, where $\psi(y)$ represents the government tuition subsidy. While such aid is, in practice, distributed through a variety of policy instruments, we follow the parsimonious approach of Benabou (2002) and model the net effect of these policies in reduced-form using the two-parameter policy schedule

$$\psi(y) = \frac{y^{\tau_n}}{1 + a_n} \tag{23}$$

where τ_n is the rate of progressivity of the need-based subsidy and $1 + a_n$ is the intercept determining the overall level of support.

Research Policies. As with tuition, government subsidization of university research is administered through several different programs and agencies, including the National Institute of Health, the Department of Defense, NASA, the National Science Foundation, and others.[34] As above, we model these programs parsimoniously through a reduced-form allocation rule for government grants that captures both the level of subsidy and its distribution across institutions. Specifically, we augment the university budget constraint (9) so that government grants cover a fraction $1-G(k)$ of a university's research (but not teaching) expenditures. The dependence of research subsidies on k reflects the meritocratic nature of government grant making and allows us to match the distribution of federal research funds observed in Figure B6. We parameterize the government's grant policy schedule using the two-parameter family

$$G(k) = \bar{G}k^{-\tau_G} \tag{24}$$

where $\bar{G}$ and τ_G capture the average subsidy and its distribution across universities.

[34]See National Science Board (2018), *Expenditures and Funding for Academic R&D*.

F Proofs of Quantitative Model

F.1 University problem

We start by solving the university's problem. We guess that in equilibrium there exists a log-linear mapping from a university teaching quality, q, to its revenue per student R, knowledge capital k, research and teaching faculty average quality $\bar{h}_R, \bar{h}_T$, student peer effect $\bar{z}$, research and teaching intermediate goods e_R, e_T: namely that there exist a set of variables m_R, m_k, m_{hR}, m_{hT}, m_z, m_{eR}, m_{eT} and χ_R, χ_k, χ_{hR}, χ_{hT}, χ_z, χ_{eR}, χ_{eT}, such that

$$\log R(q) = m_R + \chi_R(\log q - m_q) \tag{25}$$

$$\log k(q) = m_k + \chi_k(\log q - m_q) \tag{26}$$

$$\log \bar{h}_R(q) = m_{hR} + \chi_{hR}(\log q - m_q) \tag{27}$$

$$\log \bar{h}_T(q) = m_{hT} + \chi_{hT}(\log q - m_q) \tag{28}$$

$$\log \bar{z}(q) = m_z + \chi_z(\log q - m_q) \tag{29}$$

$$\log \bar{e}_R(q) = m_{eR} + \chi_{eR}(\log q - m_q) \tag{30}$$

$$\log \bar{e}_T(q) = m_{eT} + \chi_{eT}(\log q - m_q) \tag{31}$$

All the ms and χs variables are functions of time, and we will omit the time subscript whenever no confusion results.Although we directly solve for the full quantitative model described in section 5, the simpler version analyzed in section 4 corresponds to the case $\beta_c = \beta$ and $\omega_h = 0$.

The universities' value function. The first step is to simplify the recursive formulation of the value function and reformulate the college problem as a maximization problem of a static objective with two components: teaching quality and research output. We guess that the value function is log-linear in knowledge capital

$$V_t(k) = \bar{v}_t + v_t \ln k \tag{32}$$

Replacing this guess into the expression for the value function and using our guesses (26)-(28) gives

$$
\begin{aligned}
&(\bar{v}_t + v_t \ln k_t) = \ln q_t + \beta_c (\bar{v}_{t+1} + v_{t+1} \ln k_{t+1}) \\
&= \ln q_t + \beta_c v_{t+1} \left(\gamma_h \ln \bar{h}_R + \gamma_e \ln e_{Rt} + \gamma_k \ln k_t\right) + \beta_c \bar{v}_{t+1} \\
&= \ln q + \beta_c v_{t+1}(\gamma_e(m_{eRt} + \chi_{eRt}(\ln q_t - m_{qt})) + \gamma_h(m_{hRt} + \chi_{hRt}(\ln q_t - m_{qt})) + \gamma_k \ln k_t) + \beta_c \bar{v}_{t+1} \\
&= \ln q_t + \beta_c v_{t+1}((\gamma_e \chi_{eRt} + \gamma_h \chi_{hRt})(\ln q_t - m_{qt}) + \beta_c v_{t+1} \gamma_k \ln k_t + const. \\
&= (1 + \beta_c v_{t+1}(\gamma_e \chi_{eRt} + \gamma_h \chi_{hRt})) \frac{1}{\chi_{kt}} (\ln k_t - m_{kt}) + \beta_c v_{t+1} \gamma_k \ln k_t + const.
\end{aligned}
$$

Equating the terms in $\ln k_t$ from the left and right hand side of this equation gives

$$
v_t = \frac{1}{\chi_{kt}} + \beta_c \left(\gamma_k + \gamma_e \frac{\chi_{eRt}}{\chi_{kt}} + \gamma_h \frac{\chi_{hRt}}{\chi_{kt}} \right) v_{t+1} \tag{33}
$$

When all elasticities χs are constant, for example in the steady-state of the model, it simplifies to

$$
v = \frac{1}{\chi_k} \frac{1}{1 - \beta_c \left(\gamma_k + \gamma_e \frac{\chi_{eR}}{\chi_k} + \gamma_h \frac{\chi_{hR}}{\chi_k} \right)} \tag{34}
$$

An equivalent static problem. We now use these guesses to reformulate the college's problem as a maximization problem of a static objective with two components: teaching quality and research output. Given that the implied elasticity of the value function to knowledge capital v_t is independent on a college's own choices, the solutions to the original problem coincides with the solution to the following static problem

$$
\max_{q, \phi(\cdot), e_R, e_T, \mu_R(\cdot), \mu_T(\cdot)} \ln q + \beta_c v_{t+1} \ln k' \tag{35}
$$

$$
\text{subject to} \quad \ln q = \ln \bar{h}_T^{\omega_h} e_T^{\omega_e} \bar{z}^{\omega_z} k^{\omega_k} \tag{36}
$$

$$
k' = k^{\gamma_k} e_R^{\gamma_e} \bar{h}_R^{\gamma_h} \tag{37}
$$

$$\mathop{\mathbb{E}}_{\phi(.)}[p(q,z)] = G(k)\left[e_R + \int whd\mu_R(h)\right] + e_T + \int whd\mu_T(h) \tag{38}$$

$$\bar{h}_R = \int hd\mu_R(h) \tag{39}$$

$$\bar{h}_T = \int hd\mu_T(h) \tag{40}$$

$$\ln \bar{z}(\phi;p) = \mathbb{E}_{\phi(.)}[\ln(z)] - \sigma_u^2(\phi;p). \tag{41}$$

This problem has two appealing characteristics. First the weight on research is endogenous to v_{t+1} which captures the future discounted payoffs of knowledge production. Second this weight is common across all colleges.

Let s$_{eR}, s_{eT}, s_{hR}, s_{hT}$ denote the share of tuition revenues, $R = \mathbb{E}_{\phi(.)}\left[p(q,z)\right]$, spent on research and teaching equipment, $s_{eR} = G(k)e_R/R$, $s_{eT} = e_T/R$ and on research and teaching faculty wages, $s_{hR} = G(k)w\bar{h}_R/R$, $s_{hT} = w\bar{h}_T/R$. Using the definition of expenditure shares, teaching quality, q, becomes

$$\ln q = \ln \left(\mathop{\mathbb{E}}_{\phi(.)}[p(q,z)]s_{hT}/w\right)^{\omega_h}\left(\mathop{\mathbb{E}}_{\phi(.)}[p(q,z)]s_{eT}\right)^{\omega_e}\bar{z}^{\omega_z}k^{\omega_k}.$$

We now guess that tuition are log-normally distributed within a college. Denoting $\ln\tilde{R} = \mathbb{E}_{\phi(.)}[\ln p(k,z)]$ the arithmetic mean of the associated normal distribution of log tuition fees within a college, this guess implies the following equality between average tuition, the variance and the mean of log-tuitions

$$\ln R - \frac{1}{2}V_{\phi(.)}(\ln p(q,z)) = \ln \mathop{\mathbb{E}}_{\phi(.)}[p(q,z)] - \frac{1}{2}V_{\phi(.)}(\ln p(q,z)) = \mathop{\mathbb{E}}_{\phi(.)}[\ln p(q,z)] = \ln\tilde{R}.$$

We verify later that the guess that tuition are log-normally distributed within a college is true (see equation (72).

The last step before taking the first order conditions is to substitute the peer-effect (41) into the expression for teaching quality and to specify the expression for the cost of heterogeneity σ_u^2.

Assumption 1. *The cost of heterogeneity across students σ_u^2 is assumed to have the following form:*

$$\sigma_u^2(\phi; p) = \frac{\Omega_t}{2} V_{\phi(.)}(\ln p(q,z)) \quad (42)$$

$$\textit{with} \quad \Omega_t = \frac{\omega_e + \omega_h + \beta v_{t+1}(\gamma_e + \gamma_h)}{\omega_z} \quad (43)$$

This choice for Ω ensures the tractability of the college problem.

Using the expression for the cost of heterogeneity (43), the definition of the peer-effect (41) and the guess that tuition are log-normally distributed, the college problem becomes fully log-linear in tuition and student' ability

$$\max_{q,\phi(z),s_{hR},s_{hT},s_{eR},s_{eT}} \ln \left(\frac{s_{hT}\tilde{R}}{w}\right)^{\omega_h} \left(\tilde{R}s_{eT}\right)^{\omega_e} \tilde{z}^{\omega_z} k^{\omega_k} + \beta_c v_{t+1} \ln \left(\frac{\tilde{R}s_{eR}}{G(k)}\right)^{\gamma_e} \left(\frac{s_{hR}\tilde{R}}{wG(k)}\right)^{\gamma_h} k^{\gamma_k}$$

$$\text{with} \quad \ln \tilde{R} = \mathop{\mathbb{E}}_{\phi(.)}[\ln p(q,z)] \text{ and } \ln \tilde{z} = \mathop{\mathbb{E}}_{\phi(.)}[\ln z].$$

Optimal policy functions. We first derive the FOC with respect to the density of students, $\phi()$. An equilibrium where colleges are indifferent across students requires that colleges are at an interior point for all students

$$0 = (\omega_e + \omega_h + \beta v_{t+1}(\gamma_e + \gamma_h)) \ln \frac{p(q,z)}{\tilde{R}} + \omega_z \ln \frac{z}{\tilde{z}}$$

and hence that tuition be equal to

$$p(q,z) = \tilde{R} \left(\frac{z}{\tilde{z}}\right)^{-\frac{\omega_z}{\omega_e+\omega_h+\beta v_{t+1}(\gamma_e+\gamma_h)}} = R \left(\frac{z}{\bar{z}}\right)^{-\frac{\omega_z}{\omega_e+\omega_h+\beta v_{t+1}(\gamma_e+\gamma_h)}}$$

where we use $\ln \tilde{R} = \ln R - \frac{1}{2} V_\phi(\ln p(k,z)) = \ln R$ and $\ln \tilde{z} = \ln \bar{z} + \sigma_u^2(\phi; p)$ for the second equality. The elasticity of tuition to ability $\frac{\omega_z}{\omega_e+\omega_h+\beta v_{t+1}(\gamma_e+\gamma_h)}$ increases in absolue terms with the elasticity of teaching quality to student peer effects ω_z and decreases with the elasticity of teaching quality to equipment ω_e. Importantly, it is also lower when research and knowledge production are highly valued by colleges, v_{t+1}. In other words, research increases the valuation of financial resources relative to student ability.

We now consider the optimal choice of spending on research and teaching equipment and faculty wages. Taking tuition revenues R as given, we take the F.O.C. w.r.t. s_{eR}, s_{eT}, s_{hT} and s_{hR}:[35]

$$s_{eR} = \frac{\beta v_{t+1}\gamma_e}{\beta v_{t+1}(\gamma_e + \gamma_h) + \omega_e + \omega_h} \tag{44}$$
$$s_{eT} = \frac{\omega_e}{\beta v_{t+1}(\gamma_e + \gamma_h) + \omega_e + \omega_h} \tag{45}$$
$$s_{hR} = \frac{\beta v_{t+1}\gamma_h}{\beta v_{t+1}(\gamma_e + \gamma_h) + \omega_e + \omega_h} \tag{46}$$
$$s_{hT} = \frac{\omega_h}{\beta v_{t+1}(\gamma_e + \gamma_h) + \omega_e + \omega_h} \tag{47}$$

F.2 Equilibrium Tuition Schedule (Proof of Proposition 1)

Starting from the expression for tuition we just derived and using the definition of teaching quality (36), together with our guesses (25)-(31), one gets

$$\begin{aligned}
p(q,z) &= R\left(\frac{z}{\bar{z}}\right)^{-\frac{\omega_z}{\omega_e+\omega_h+\beta_c v(\gamma_e+\gamma_h)}} \\
&= R\left[\bar{h}_T^{\omega_h} e_T^{\omega_e} \bar{z}^{\omega_z} k^{\omega_k}\right]^{\frac{1}{\omega_e+\omega_h+\beta_c v(\gamma_e+\gamma_h)}} \left(\bar{h}_T^{\omega_h} e_T^{\omega_e} k^{\omega_k}\right)^{\frac{-1}{\omega_e+\omega_h+\beta_c v(\gamma_e+\gamma_h)}} z^{-\frac{\omega_z}{\omega_e+\omega_h+\beta_c v(\gamma_e+\gamma_h)}} \\
&= \bar{p} q^{\frac{1}{\omega_e+\omega_h+\beta_c v(\gamma_e+\rho_h)}+\chi_R-\frac{(\omega_e+\omega_h)\chi_R}{\omega_e+\omega_h+\beta_c v(\gamma_e+\gamma_h)}-\chi_k\frac{\omega_k}{\omega_e+\omega_h+\beta_c v(\gamma_e+\gamma_h)}} z^{-\frac{\omega_z}{\omega_e+\omega_h+\beta_c v(\gamma_e+\gamma_h)}} \\
&= \bar{p} q^{\frac{1}{\epsilon_1}} z^{-\frac{\epsilon_2}{\epsilon_1}}
\end{aligned} \tag{48}$$

[35]The assumption that tuition revenues are not affected by the choice of spending relies on the notion that once students are sorted through colleges and paid for their tuition, they cannot leave the college even if the latter were to deviate from its equilibrium choices of s_{eR}, s_{eT} and s_{hR} and therefore deviate from its promised quality of education. We believe that this assumption is realistic, since applying and moving for colleges is very costly. Note that the notion that students will not leave their college doesn't mean that students are deceived, since they form rational expectations *ex ante* about the equilibrium.

where we have defined the following aggregate endogenous variables:

$$\log \bar{p} = \frac{\left(\beta_c v(\gamma_e+\gamma_h)m_R - \omega_k m_k - \left(\frac{\omega_e+\omega_h+\beta_c v(\gamma_e+\gamma_h)}{\epsilon_1} - 1\right) m_q - \log\left(s_{eT}\right)^{\omega_e}\left(\frac{s_{hT}}{w}\right)^{\omega_h}\right)}{\omega_e+\omega_h+\beta_c v\left(\gamma_e+\gamma_h\right)} \tag{49}$$

$$\epsilon_1 = \frac{\omega_e+\omega_h+\beta_c v\left(\gamma_e+\gamma_h\right)}{1+\chi_R\beta_c v\left(\gamma_e+\gamma_h\right) - \chi_k\omega_k} \tag{50}$$

$$\epsilon_2 = \frac{\omega_z}{1+\chi_R\beta_c v\left(\gamma_e+\gamma_h\right) - \chi_k\omega_k} \tag{51}$$

where we use $w\bar{h}_T = s_{hT}R$, $e_T = s_{eT}R$, (25), and (26).

F.3 Household problem in section 4 (Proof of Propositions 2 and 3)

In this section, we derive the expression for the optimal spending rate of household on tuition shown in proposition 2. The derivation of the spending rate in the full quantitative model is given in the next section.

Using equation (10), the household problem is given by

$$\begin{aligned} U(h,z) &= \max_{c,q,h'} \ln c + \beta \mathbb{E} U(h',z') \\ \text{s.t.} \quad c + \bar{p} q^{\frac{1}{\epsilon_1}} z^{-\frac{\epsilon_2}{\epsilon_1}} &= wh \\ \text{and} \quad \ln h' &= \ln z + \alpha \ln q \end{aligned}$$

We guess that $U(h,z) = \bar{u} + u\ln h + u_z \ln z$ and we denote s the fraction of their income households spend on tuition $\bar{p} q^{\frac{1}{\epsilon_1}} z^{-\frac{\epsilon_2}{\epsilon_1}} = swh$ and thereby $c = (1-s)wh$. It follows from the latter that

$$\ln q = \epsilon_1 \ln(swh) - \epsilon_1 \ln \bar{p} + \epsilon_2 \ln z \tag{52}$$

and combining with the guess on the value functions gives

$$\begin{aligned} \bar{u} + u\ln h + u_z \ln z &= \ln((1-s)wh) + \beta(\bar{u} + u\ln h' + u_z \mathbb{E}\ln z') \\ &= \ln((1-s)wh) + \beta(\bar{u} + u\ln z + u\alpha \ln q + u_z \mathbb{E}\ln z') \end{aligned}$$

$$= \ln((1-s)wh) + \beta(\bar{u} + u\ln z + u\alpha(\epsilon_1 \ln(swh) - \epsilon_1 \ln \bar{p} + \epsilon_2 \ln z)) - \beta u_z \frac{\sigma_z^2}{2}.$$

where we use $\ln z' \sim (-\sigma_z^2/2, \sigma_z^2)$ in the last term.

Comparing the coefficients on $\ln h$ we obtain the following condition on u

$$u = 1 + \beta u \alpha \epsilon_1.$$

The next step is to take the first order with respect to s. It is given by

$$\frac{1}{1-s} = \beta u \alpha \epsilon_1 \frac{1}{s}$$

and thus

$$s = \frac{\beta u \alpha \epsilon_1}{1 + \beta u \alpha \epsilon_1}.$$

Since s is independent of h and z, the guess on the value function is correct.

Finally, using the expression for u, we obtain

$$s = \frac{\beta u \alpha \epsilon_1}{1 + \beta u \alpha \epsilon_1} = \beta \alpha \epsilon_1. \tag{53}$$

F.4 Household problem in the quantitative model

We now solve for the optimal spending of households on tuition in the full quantitative model. We start by giving the timing of a lifetime in detail. A period corresponds to four years. Each individual lives for five periods as a child, then attends college for one period, and finally works as an adult for ten periods, which we index by $a \in \{1, ..10\}$. Each adult has one child when they are in their fifth period of adult life, $a = 5$, and sends them to college before retiring at $a = 10$. Parents retire after their children graduate from college, so that parents and children do not overlap in the labor market. For simplicity, we assume that $r = 1/\delta - 1$.

The household problem can be formulated recursively as

$$U(h,z)=\max_{c_a,q}\left\{\left[\sum_{a=1}^{10}\delta^{a-1}\ln c_a\right]+\beta\mathbb{E}\left[U(h',z')\right]\right\} \tag{54}$$

where δ and β are the time and intergenerational discount factor, respectively.

Denoting $c_{t,a}$ is the consumption of an individual whose age is a at time t, the household's life-time income and budget constraint are given by:

$$\sum_{a=1}^{10}\delta^{a-1}(1+a_{ct+a-1})c_{t+a-1,a}+\delta^{10-1}\frac{y^{\tau_n}}{1+a_n}p_{t+10-1}(q,z):=(1-a_y)h^{1-\tau_y}\sum_{a=1}^{10}\delta^{a-1}w_{t+a-1}^{1-\tau_y}$$

where $(1-a_y)\left(w_t h\right)^{1-\tau_y}$ is the after tax-and-transfers labor earnings in a given period.

We define the lifetime after-tax income y_t and lifetime before-tax wage per unit of human capital $\tilde{w}_t$ as

$$y_t=(1-a_y)(\tilde{w}_t h)^{1-\tau_y}$$

$$\text{with}\quad \tilde{w}_t=\left(\delta^{-9}\sum_{a=1}^{10}\delta^{a-1}w_{t+a-1}^{1-\tau_y}\right)^{\frac{1}{1-\tau_y}}$$

We first solve for the optimal allocation of consumption across periods of an adult's lifetime. From the assumption that $r=1/\delta-1$, after-tax consumption is constant within one's lifetime:

$$(1+a_{c,t+a-1})c_{t+a-1,a}=\delta^{a-1}\Pi_{\tau=1}^{a-1}(1+r_{t+\tau})(1+a_{ct})c_{t1}=(1+a_{ct})c_{t1}$$

Hence the problem of the household can be written more simply as

$$U(h,z)=\max_{c,q}\left\{\ln c\sum_{a=1}^{10}\delta^{a-1}+\beta\mathbb{E}\left[U(h',z')\right]\right\} \tag{55}$$

$$\text{s.t.} \quad y = \delta^{-9}(1 + a_{ct})c \sum_{a=1}^{10} \delta^{a-1} + \frac{y^{\tau_n}}{1 + a_n} p_{t+10}(q, z) \tag{56}$$

For the next step it is useful to first derive the sorting rule (12). We combine the expression for tuition (48) and financial aid (23) and we denote s the share of net income that households spend on tuition $\bar{p} q^{\frac{1}{\epsilon_1}} z^{-\frac{\epsilon_2}{\epsilon_1}} = s(1 + a_n) y^{1-\tau_n}$. Hence, the sorting rule is given by

$$q = \left(\frac{s(1 + a_n) y^{1-\tau_n}}{\bar{p}} \right)^{\epsilon_1} z^{\epsilon_2} \tag{57}$$

We guess that the value function is a log-linear function of h and z: $U(h, z) = \tilde{U}(h, \xi) = u_t \ln h_t + u_{zt} \ln \xi + \bar{u}_t$ with $u_t, u_{zt}, \bar{u}_t$ three endogenous and aggregate variables. Recall that ξ denotes the shock to the transmission of human capital from parents to child given in equation (22). Like in section (F.3), we use this guess to substitute for the value function in the current and future period in equation (55) and we find that a necessary condition is that u_t obeys the following forward difference equation:

$$u_t = (1 - \tau_y) \sum_{a=1}^{10} \delta^{a-1} + \beta u_{t+10} \rho_t$$
$$\text{with} \quad \rho_t = \varphi + \alpha \left[\epsilon_{2t} \varphi + \epsilon_{1t} (1 - \tau_n)(1 - \tau_y) \right]$$

where we have used the sorting rule (57).

Like in section (F.3), we then take the derivative of the right hand side of the value function with respect to s which gives

$$s_t = \frac{\beta \alpha \epsilon_{1t} (1 - \tau_n) u_{t+10}}{\sum_{a=1}^{10} \delta^{a-1} + \beta \alpha \epsilon_{1t} (1 - \tau_n) u_{t+10}} \tag{58}$$

and s_t is independent of h and z and the guess on the policy function is correct.

One can easily check that the expression for s obtained in equation (53) corresponds to the special case with $\phi = \tau_n = \tau_y = 0$.

Law of accumulation of human capital. We start by defining the elasticity of college quality to income ϵ_I and ability ϵ_A. They capture the strength of the income-sorting and ability-sorting channel taking into account the progressivity of taxes and financial aid:

$$\epsilon_I \equiv \epsilon_1(1-\tau_n)(1-\tau_y) \tag{59}$$

$$\epsilon_A \equiv \varphi\epsilon_2 \tag{60}$$

Notice that when there is no income tax and financial aid, the income-sorting coefficient simplifies and becomes $\epsilon_I = \epsilon_1$.

Taking the log of the sorting rule (57) and using the previous definitions (59), (60) and ias well as the transmission of human capital over generation $z = \xi h^{\varphi}$, the optimal college is given by

$$\ln q = \epsilon_1(C_h - \ln \bar{p}) + (\epsilon_I + \epsilon_A)\ln h + \epsilon_2 \ln \xi \tag{61}$$

$$\text{with} \quad C_h \equiv \ln\left(s(1+a_n)\tilde{w}^{(1-\tau_y)(1-\tau_n)}(1-a_y)^{(1-\tau_n)}\right). \tag{62}$$

Note that, in the simpler model without policies and life-cycle, $C_h = \ln s + \ln h$.

Replacing this expression in the law of accumulation of human capital given by (4) we obtain

$$\ln h' = \alpha(\epsilon_1(C_h - \ln \bar{p}) + (\epsilon_I + \epsilon_A)\ln h + \epsilon_2 \ln \xi) + \varphi \ln h + \ln \xi. \tag{63}$$

F.5 Equilibrium distributions of human capital and universities intangible capital

Law of motion of the distribution of human capital We denote m_{hta} and Σ_{hta} the mean and standard deviation of the log of human capital of adults with age a at time t. We denote m_{ht}, Σ_{ht} the mean and standard deviation of the log of human capital of the parents who are currently sending their child to college, namely those with $a = 10$:

$$m_{ht} = m_{ht10}$$
$$\Sigma_{ht} = \Sigma_{ht10}$$

From these definitions and the law of motion of human capital at the individual level (63) we have that the law of motion of the distribution of human capital across households is given by

$$\ln h_{t+1,a} \sim \mathcal{N}\left(m_{h,t+1,a+1}, \Sigma^2_{ht+1,a+1}\right) \tag{64}$$

$$m_{h,t+1,a+1} = m_{h,t,a} \qquad \text{for} \quad a < 10 \tag{65}$$

$$\Sigma_{h,t+1,a+1} = \Sigma_{h,t,a} \qquad \text{for} \quad a < 10 \tag{66}$$

$$m_{h,t+1,1} = \rho_t m_{ht} - (\alpha\epsilon_{2t} + 1)\frac{\sigma_z^2}{2} + \alpha\epsilon_{1t}(C_{ht} - \ln \bar{p}_t) \qquad \text{for} \quad a = 10 \tag{67}$$

$$\Sigma^2_{h,t+1,1} = \rho_t^2 \Sigma^2_{ht} + \sigma_y^2 + (\varphi(\alpha\epsilon_{2t} + 1))^2 \sigma_z^2 \qquad \text{for} \quad a = 10 \tag{68}$$

where $\rho_t = \varphi + \alpha\left[\epsilon_{2t}\varphi + \epsilon_{1t}(1 - \tau_n)(1 - \tau_y)\right]$

It is intuitive that the shifter C_{ht} in the law of motion of the mean of the distribution (67) is increasing in the saving rate s_t, in the average education subsidies a_n but decreasing in the intercept of the tuition schedule $\bar{p}_t$. From the expression given by (49), the latter is increasing in the share of resources devoted to research. Finally, the persistence coefficient ρ_t is decreasing in the progressivity of financial aid τ_n.

This also confirms that human capital is log-normally distributed on the transition path as well as in steady state as long as the initial distribution is log-normal.

Distribution of college quality. From (61), it follows that the distribution of college quality is given by

$$\ln q \sim \mathcal{N}\left((\epsilon_I+\epsilon_A)m_h+\epsilon_1(C_h-\log\bar{p})-\epsilon_2\frac{\sigma_z^2}{2}, \epsilon_2^2\sigma_z^2+(\epsilon_I+\epsilon_A)^2\Sigma_h^2\right) \quad (69)$$

Thus

$$m_q=(\epsilon_I+\epsilon_A)m_h+\epsilon_1(C_h-\log\bar{p})-\epsilon_2\frac{\sigma_z^2}{2}. \quad (70)$$

College quality is log-normally distributed on the transition path as well as in steady state.

Within college parental income distribution. Using (61), we now solve for the conditional distribution of parental human capital within a college, which is given by

$$\ln h|q \sim \mathcal{N}\left(m_{h|q}, \sigma_{h|q}^2\right)$$

where

$$m_{h|q}=s_z m_h+(1-s_z)\frac{\left(\ln q-\epsilon_1(C_h-\log\bar{p})+\epsilon_2\frac{\sigma_z^2}{2}\right)}{\epsilon_I+\epsilon_A}$$
$$\sigma_{h|q}^2=s_z\Sigma_h^2$$

$$\text{with} \quad s_z=\frac{\epsilon_2^2\sigma_z^2}{(\epsilon_I+\epsilon_A)^2\Sigma_h^2+\epsilon_2^2\sigma_z^2} \quad (71)$$

where s_z is the share of the variance not explained by parent's human capital.

Parental income within a college is log-normally distributed in transition as well as in steady state. The distribution function is defined as $\phi_h(h|q)$.

Notice that

$$\mathbb{E}(m_{h|q})=m_h.$$

Within college student ability distribution. From the definition of abilities $\ln z = \varphi \ln h + \ln \xi$ and the sorting rule used above $\ln q = (\epsilon_I + \epsilon_A) \ln h + \epsilon_2 \ln \xi + \epsilon_1 (C_h - \log \bar{p})$, one gets

$$\ln z = \frac{1}{\epsilon_2} \left(\ln q - \epsilon_I \ln h - \epsilon_1 (C_h - \log \bar{p})\right) \tag{72}$$

$$\Rightarrow \ln z | q \sim \mathcal{N}\left(\frac{1}{\epsilon_2}\left(\ln q - \epsilon_I m_{h|q} - \epsilon_1 (C_h - \log \bar{p})\right), \left(\frac{\epsilon_I}{\epsilon_2}\right)^2 \sigma^2_{h|q}\right) \tag{73}$$

Since $\ln p(q,z) = \ln \bar{p} + \frac{1}{\epsilon_1} \ln q - \frac{\epsilon_2}{\epsilon_1} \ln z$, tuition are log-normally distributed within a college and its variance is common across universities.

Distribution of tuition revenues. The average tuition revenue of a college is the mean of tuition paid by households in this college. All households pay the same share of their income, hence using the distribution of income within a college, one gets that the mean tuition is

$$\begin{aligned}
R(q) &= \int p(q,z) \phi(z|q) dz \\
&= \int s(1+a_n)(1-a_y)^{1-\tau_n} \left(\tilde{w} h\right)^{(1-\tau_y)(1-\tau_n)} \phi_h(h|q) dh \\
\ln R(q) &= C_h + (1-\tau_y)(1-\tau_n) m_{h|q} + \frac{((1-\tau_y)(1-\tau_n))^2 \sigma^2_{h|q}}{2} \\
&= C_h + (1-\tau_y)(1-\tau_n) \left[s_z m_h + (1-s_z) \frac{\ln q - \epsilon_1 (C_h - \log \bar{p}) + \epsilon_2 \frac{\sigma_z^2}{2}}{\epsilon_I + \epsilon_A} \right] \\
&+ \frac{((1-\tau_y)(1-\tau_n))^2 \sigma^2_{h|q}}{2}
\end{aligned}$$

This also verifies our guess (25). Finally these results enables us to get an expression for the distribution of revenue per student across colleges:

$$\ln R \sim \mathcal{N}\left(m_R, \Sigma_R^2\right) \tag{74}$$

$$m_R = C_h + \frac{((1-\tau_y)(1-\tau_n))^2 \sigma^2_{h|q}}{2} + (1-\tau_y)(1-\tau_n) m_h \tag{75}$$

$$\Sigma_R^2 = \chi_R^2 \left[\epsilon_2^2 \sigma_z^2 + (\epsilon_I + \epsilon_A)^2 \Sigma_h^2\right] \tag{76}$$

College tuition revenue is log-normally distributed on the transition path as well as in steady state.

Identifying coefficients with the guess, one gets:

$$\chi_R = (1-\tau_y)(1-\tau_n)(1-s_z)\frac{1}{\epsilon_I + \epsilon_A}$$

Combining this with equations (71) and (76),

$$\Sigma_R = (1-\tau_y)(1-\tau_n)\sqrt{1-s_z}\Sigma_h. \tag{77}$$

If there is no peer effect ($\omega_z = 0$) and $\epsilon_A = 0$, then $s_z = 0$ and Σ_R is proportional to Σ_h. With the peer effect, as Σ_h decreases, s_z decreases. Intuitively, there is more mix of students from different family backgrounds within colleges as the peer effect becomes stronger and total revenue of colleges get less dispersed.

Verification of guesses. From the definition of $\ln \bar{z}$ and equation (73),

$$\ln \bar{z} = \frac{1}{\epsilon_2}\left(\ln q - \epsilon_I m_{h|q} - \epsilon_1 (C_h - \log \bar{p})\right) - \frac{\Omega}{2}\left(\frac{\epsilon_I}{\epsilon_1}\right)^2 \sigma_{h|q}^2.$$

Thus (29) is verified. From the technology for college quality

$$\ln q = \ln \left(R s_{hT}/w\right)^{\omega_h} \left(R s_{eT}\right)^{\omega_e} \bar{z}^{\omega_z} k^{\omega_k},$$

equation (29) and (25), our guess (26) is also verified. From $s_{eR} = G(k) e_R / R$, $s_{eT} = e_T/R$, $s_{hR} = G(k) w \bar{h}_R / R$, $s_{hT} = w\bar{h}_T/R$, equations (27), (28), (30), (31) are also verified. This verifies that all college-specific variables are log-linear functions of quality q and log-normally distributed.

Law of motion of knowledge capital From the law of motion of capital, we obtain

$$\begin{aligned}\ln k_{t+1} &= \ln e_{Rt}^{\gamma_e} \bar{h}_{Rt}^{\gamma_h} k^{\gamma_k} \\ &= \ln \left(\frac{s_{eRt}}{G_t} \right)^{\gamma_e} \left(\frac{s_{hRt}}{w_t G_t} \right)^{\gamma_h} + (\gamma_e + \gamma_h) \ln R_t + (\gamma_k + \tau_G(\gamma_e + \gamma_h)) \ln k_t\end{aligned}$$

We denote m_R and Σ_R (m_k and Σ_k) the mean and standard deviation of log-income (log-knowledge capital) across colleges. Taking the mean and variance of the law of motion above gives that if knowledge capital is log-normally distributed, then it remains log-normally distributed and the law of motion of the mean and the variance of the associated normal distribution are given by the following proposition.

Proposition 7. *Assume knowledge capital is log-normally distributed in the first period. It is log-normally distributed along the transition path. The law of motion of the distribution of knowledge capital across colleges is given by*

$$\ln k_{it} \sim \mathcal{N}\left(m_{kt}, \Sigma_{kt}^2\right) \tag{78}$$

$$m_{kt+1} = \ln \left(\frac{s_{eRt}}{G_t} \right)^{\gamma_e} \left(\frac{s_{hRt}}{w_t G_t} \right)^{\gamma_h} + (\gamma_e + \gamma_h) m_{Rt} + (\gamma_k + \tau_G(\gamma_e + \gamma_h)) m_{kt} \tag{79}$$

$$\Sigma_{kt+1} = (\gamma_k + \tau_G(\gamma_e + \gamma_h))\Sigma_{kt} + (\gamma_e + \gamma_h)\Sigma_{Rt} \tag{80}$$

where we used the fact, that in the equilibrium we look at, (log) income and (log) knowledge are perfectly correlated $cov\,(\ln R, \ln k) = \sqrt{\Sigma_R^2 \Sigma_k^2} = \Sigma_R \Sigma_k$.

F.6 Law of motion for m_k, m_h - Simplification

We now express the laws of motion of the distribution of knowledge capitals and human capital in a compact format.[36]

$$m_{kt+1} = \gamma_{kkt} m_{kt} + \gamma_{kht} m_{ht} + \gamma_{kt} \tag{81}$$

$$m_{h,t+1,1} = \gamma_{hht} m_{ht} + \gamma_{hkt} m_{kt} + \gamma_{ht} \quad \text{for} \quad a = 10 \tag{82}$$

$$m_{h,t+1,a+1} = m_{h,t,a} \quad \text{for} \quad a < 10 \tag{83}$$

with

$$\gamma_{kkt} = \gamma_K + (\gamma_e + \gamma_h)\tau_G \tag{84}$$

$$\gamma_{kht} = (\gamma_e + \gamma_h)(1 - \tau_y)(1 - \tau_n) \tag{85}$$

$$\gamma_{kt} = \ln \left(\frac{s_{eR}}{G}\right)^{\gamma_e} \left(\frac{s_{hR}}{wG}\right)^{\gamma_h} + (\gamma_e + \gamma_h) \left[C_h + \frac{((1-\tau_y)(1-\tau_n))^2 \sigma^2_{h|q}}{2}\right] \tag{86}$$

$$\gamma_{hht} = (1 - \tau_y)(1 - \tau_n)\alpha(\omega_e + \omega_h) + \varphi(1 + \alpha\omega_z) \tag{87}$$

$$\gamma_{hkt} = \alpha\omega_k \tag{88}$$

$$\begin{aligned} \gamma_{ht} = & -(1 + \alpha\omega_z)\frac{\sigma_z^2}{2} + \alpha(\omega_e + \omega_h)C_h \\ & - \alpha\beta_c v(\gamma_e + \gamma_h)\frac{((1-\tau_y)(1-\tau_n))^2 \sigma^2_{h|q}}{2} + \alpha \left[\ln (s_{eT})^{\omega_e} \left(\frac{s_{hT}}{w}\right)^{\omega_h}\right] \end{aligned} \tag{89}$$

We now briefly give an intuition for each term from (84)-(89). Looking at equation (84), current average knowledge capital has a strong effect on future knowledge capital when knowledge depreciates slowly (low γ_k). Looking at equation (85), current average human capital has a strong effect on future average knowledge capital when fundamental research is intensive in equipment and faculty ($\gamma_e + \gamma_h$). Looking at equation (86), the growth of fundamental knowledge is high when the rate of cross-subsidization is

[36] Recall that

$$m_{kt+1} = \ln \left(\frac{s_{eR}}{G}\right)^{\gamma_e} \left(\frac{s_{hR}}{wG}\right)^{\gamma_h} + (\gamma_e + \gamma_h) m_{Rt} + (\gamma_k + \tau_G(\gamma_e + \gamma_h)) m_{kt}$$

where m_R in the first line is given by equation (75).

high (s_{eR}, s_{hR}) or when households spend a large share of their income on tuition, s.

Looking at equation (87), current average human capital has a strong effect on future human capital when the transmission of of abilities from parents to children is strong (φ), the peer effect and the effect of teaching equipment and faculty is high ($\omega_z, \omega_e, \omega_h$). Looking at equation (88), current average knowledge capital has a strong effect on future human capital when knowledge capital matters a lot for teaching equality ω_q. Finally, looking at equation (89), the growth of human capital is high when household spend a significant share of their income on tuition s and universities spend a lot on teaching equality s_{eT}, s_{hT}.

Expressing $\bar{p}$ as a function of m_h and m_k. From the earlier expression for $\bar{p}$ given by equation (49), and using the expressions for the mean of college quality (70), and college revenues (75), we obtain

$$\epsilon_1 \log \bar{p} = (\epsilon_1 - (\omega_e + \omega_h))(C_h + (1-\tau_y)(1-\tau_n)m_h) + \beta_c v(\gamma_e + \gamma_h)\left(\frac{((1-\tau_y)(1-\tau_n))^2\sigma^2_{h|q}}{2}\right) - \omega_k m_k - \left(\frac{\omega_e + \omega_h + \beta_c v\,(\gamma_e + \gamma_h)}{\epsilon_1} - 1\right)\left(\epsilon_A m_h - \epsilon_2 \frac{\sigma_z^2}{2}\right) - \log\,(s_e)^{\omega_e}\left(\frac{s_h}{w}\right)^{\omega_h} \tag{90}$$

Now we discuss the intuition of this equation. For exposition, consider the simpler model in section 3. Then this equation becomes

$$\epsilon_1 \log \bar{p} = (\epsilon_1 - \omega_e)(C_h + m_h) + \beta v \gamma_e \left(\frac{\sigma^2_{h|q}}{2}\right) - \omega_k m_k - \left(\frac{\omega_e + \beta v \gamma_e}{\epsilon_1} - 1\right)\left(-\epsilon_2 \frac{\sigma_z^2}{2}\right) - \omega_e \log s_e$$

Organizing this equation,

$$\omega_k m_k + \omega_e(\ln s_e + C_h + m_h + \frac{\sigma^2_{h|q}}{2}) - (\omega_e + \beta v \gamma_e)\left(\frac{\sigma^2_{h|q}}{2}\right) - \epsilon_2\left(\frac{\omega_e + \beta v \gamma_e}{\epsilon_1}\right)\frac{\sigma_z^2}{2}$$

$$= \epsilon_1(C_h + m_h) - \epsilon_1 \log \bar{p} - \epsilon_2 \frac{\sigma_z^2}{2}$$

From (50), (51), and (75),

$$\omega_k m_k + \omega_e(\ln s_e + m_R) - (\omega_e + \beta v \gamma_e)\left(\frac{\sigma_{h|q}^2}{2}\right) - \omega_z \frac{\sigma_z^2}{2} = \epsilon_1(\ln s + m_h) - \epsilon_1 \log \bar{p} - \epsilon_2 \frac{\sigma_z^2}{2} \tag{91}$$

Since $m_{\bar{z}} = E[\ln \bar{z}] = E[E_{\phi(\cdot)}[\ln z]] - \sigma_u^2(\phi; p)$ and the mean of $\ln z$ and from(42),

$$m_{\bar{z}} = -\frac{\sigma_z^2}{2} - \frac{1}{2}\frac{\omega_e + \beta v \gamma_e}{\omega_z} V_{\phi(\cdot)}(\ln p(q, z)) = -\frac{\sigma_z^2}{2} - \frac{1}{2}\frac{\omega_e + \beta v \gamma_e}{\omega_z} V_{\phi(\cdot)}\left(\frac{\epsilon_2}{\epsilon_1}\ln z\right)$$

From (73),

$$m_{\bar{z}} = -\frac{\sigma_z^2}{2} - \frac{\omega_e + \beta v \gamma_e}{\omega_z}\frac{\sigma_{h|q}^2}{2}$$

Plugging this into (91) and from (61),

$$\omega_k m_k + \omega_e(\ln s_e + m_R) + \omega_z m_{\bar{z}} = \epsilon_1(\ln s + \ln w + m_h) - \epsilon_1 \log \bar{p} - \epsilon_2 \frac{\sigma_z^2}{2} \tag{92}$$

The left hand side is the mean supply of log quality of colleges m_q, where the first, second, and third terms are the mean contributions of log intangible capital, teaching expenditure, and the peer effect. The right hand side is the mean demand of log quality from taking log and the mean of (12). $\log \bar{p}$ is determined to balance the supply and demand of mean quality of colleges.

F.7 Proof of Proposition 4

Following our guess for the value function (32), in steady-state it is given by $V(k) = \bar{v} + v \ln k$. Substituting this guess into the recursive formulation of the value function $V(k) = \ln q + \beta V(k')$ and differentiating the latter with respect to $\ln k$ gives

$$v = \frac{d \ln q}{d \ln k} + \beta v \frac{d \ln k'}{d \ln k} = \frac{\Sigma_q}{\Sigma_k} + \beta v$$

From our guess (26) it follows that

$$\frac{d\ln q}{d\ln k} = \frac{1}{\chi_k} = \frac{\Sigma_q}{\Sigma_k}.$$

Combining both equations gives

$$v = \frac{\Sigma_q/\Sigma_k}{1-\beta}$$

Substituting this expression of v in equation (44) (and also substituting $\omega_h = 0$ and $\gamma_h = 0$) gives

$$s_R = \frac{\beta v \gamma_e}{\beta v \gamma_e + \omega_e} = \frac{\beta\gamma_e(\Sigma_q/\Sigma_k)}{(1-\beta)\omega_e + \beta\gamma_e(\Sigma_q/\Sigma_k)}$$

We now find an expression for $\frac{\Sigma_q}{\Sigma_k}$ as a function of $\frac{\Sigma_R}{\Sigma_k}$ and $\frac{\Sigma_{\bar{z}}}{\Sigma_k}$. We start from the production function of quality of education $\ln q = \omega \ln k + \omega_e \ln e_T + \omega_z \ln \bar{z}$. Using $e_T = (1-s_R)R$, and taking the variances of both sides, we get

$$\Sigma_q = \omega_k\Sigma_k + \omega_e\Sigma_R + \omega_z\Sigma_{\bar{z}}.$$

where we used the fact that $\ln k$, $\ln e_T$, and $\ln \bar{z}$ are perfectly correlated. Dividing both sides by Σ_k gives

$$\frac{\Sigma_q}{\Sigma_k} = \omega_k + \omega_e\frac{\Sigma_R}{\Sigma_k} + \omega_z\frac{\Sigma_{\bar{z}}}{\Sigma_k}.$$

F.8 Proof of Proposition 6: the case of $\omega_z = 0$.

We begin with solving for the standard deviation of university intangible capital and household human capital. Let's start with the law of motion of the variance of knowledge.

$$\Sigma_{kt+1} = \gamma_k\Sigma_k + \gamma_e\Sigma_R$$

We now turn to the standard deviation of human capital, Σ_h. When there is no peer effect, the variance of college income is equal to the variance of household income $\Sigma_R = \Sigma_h$. The solution is

$$\frac{\Sigma_k}{\Sigma_h} = \frac{\gamma_e}{1-\gamma_k}.$$

From Propositions 2 and 3,

$$\sqrt{\epsilon_1^2 \frac{\Sigma_h^2}{\Sigma_k^2} + \epsilon_2^2 \frac{\sigma_z^2}{\Sigma_h^2}} = \omega_k + \omega_e \frac{\Sigma_R}{\Sigma_k} + \omega_z \frac{\Sigma_{\bar{z}}}{\Sigma_k},$$

$$\frac{\epsilon_2}{\epsilon_1} = \frac{\omega_z}{\omega_e + \beta(1-\beta)^{-1}\gamma_e(\Sigma_q/\Sigma_k)}.$$

Since $\omega_z = 0$, the latter becomes

$$\epsilon_2 = 0$$

and the former becomes

$$\epsilon_1 \frac{\Sigma_h}{\Sigma_k} = \omega_k + \omega_e \frac{\Sigma_R}{\Sigma_k} = \omega_k + \omega_e \frac{\Sigma_h}{\Sigma_k}.$$

In addition, from equation (12), we have

$$\Sigma_q = \epsilon_1 \Sigma_h$$

Combining the last two equations gives

$$\epsilon_1 = \omega_k \frac{\Sigma_k}{\Sigma_h} + \omega_e = \omega_k \frac{\gamma_e}{1-\gamma_k} + \omega_e. \tag{93}$$

Since $h' = zq^\alpha$ and $\Sigma_q = \epsilon_1 \Sigma_h$ and z and h are independent, we get

$$\Sigma_h^2 = \sigma_z^2 + \alpha^2 \Sigma_q^2 = \sigma_z^2 + \alpha^2 \epsilon_1^2 \Sigma_h^2$$

which gives

$$\Sigma_h^2 = \frac{\sigma_z^2}{1-\alpha^2\left(\omega_k\frac{\gamma_e}{1-\gamma_k}+\omega_e\right)^2}.$$

We now solve for the mean of the distribution of human capital m_h and of university knowledge capital m_k. First note that the average tuition revenue is a simple function of the spending rate on tuition s and the average household human capital:

$$m_R = \ln(sw) + m_h.$$

Taking the mean of the log of equation (10) and using $swh = p(q,z)$, we get

$$m_R = E[\ln p(q,z)] = \ln\bar{p}+\frac{1}{\epsilon_1}m_q-\frac{\epsilon_2}{\epsilon_1}m_z = \ln\bar{p}+\frac{1}{\epsilon_1}(\omega_k m_k+\omega_e\ln(1-s_R)+\omega_e m_R+\omega_z m_{\bar{z}})-\frac{\epsilon_2}{\epsilon_1}m_z$$

Since $\omega_z = 0$ and $\epsilon_2 = 0$, one gets

$$m_R = \ln\bar{p}+\frac{1}{\epsilon_1}(\omega_k m_k+\omega_e m_R+\omega_e\ln(1-s_R))$$

which gives

$$\ln\bar{p} = \left(1-\frac{\omega_e}{\epsilon_1}\right)m_R-\frac{\omega_k}{\epsilon_1}m_k-\frac{\omega_e}{\epsilon_1}\ln(1-s_R).$$

Using the law of accumulation of human capital $h' = zq^\alpha$

$$\ln h' = \ln z+\alpha\ln q = \ln z+\alpha\epsilon_1(\ln(sw)+\ln h-\ln\bar{p})$$

and taking the expectation of both sides gives

$$m_h = -\frac{\sigma_z^2}{2}+\alpha\epsilon_1(\ln(sw)+m_h-\ln\bar{p}) = -\frac{\sigma_z^2}{2}+\alpha\epsilon_1(m_R-\ln\bar{p})$$

Using the law of accumulation of university capital,

$$m_k = \gamma_e \ln s_R + \gamma_e m_R + \gamma_k m_k = \gamma_e \ln s_R + \gamma_e(\ln(sw) + m_h) + \gamma_k m_k,$$

it follows that

$$m_k = \frac{\gamma_e \ln s_R + \gamma_e m_R}{1-\gamma_k}.$$

Substituting these expressions into our earlier expression for $\bar{p}$ gives

$$\begin{aligned}
\ln \bar{p} &= \left(1 - \frac{\omega_e}{\epsilon_1}\right) m_R - \frac{\omega_k}{\epsilon_1} \frac{\gamma_e \ln s_R + \gamma_e m_R}{1-\gamma_k} - \frac{\omega_e}{\epsilon_1} \ln(1-s_R) \\
&= \left(1 - \frac{\omega_e}{\epsilon_1} - \frac{\omega_k}{\epsilon_1} \frac{\gamma_e}{1-\gamma_k}\right) m_R - \frac{\omega_k}{\epsilon_1} \frac{\gamma_e}{1-\gamma_k} \ln s_R - \frac{\omega_e}{\epsilon_1} \ln(1-s_R) \\
&= -\frac{\omega_k \frac{\gamma_e}{1-\gamma_k} \ln s_R + \omega_e \ln(1-s_R)}{\omega_k \frac{\gamma_e}{1-\gamma_k} + \omega_e}
\end{aligned}$$

where the last line uses equation (93).

F.9 Government budget constraints

We denote $\bar{G}$ the average spending on research grants (per student), $\bar{a}_y$ and $\bar{a}_n$ the average tax rate on income and the average rate of tuition subsidy. These are three parameters that we calibrate. The following equations pin down the endogenous value of the intercepts of the research grant schedule G, of the income tax schedule a_y and of the financial aid schedule a_n respectively:

$$\bar{G} = \mathbb{E}_j \left[\left[1 - G k_j^{-\tau_G}\right] \left(e_{Rj} + \mathbb{E}_{\mu_{Rj}(.)}\left[wh\right]\right)\right] \tag{94}$$

$$(1-\bar{a}_y) \int wh_{Ri} di = \int (1-a_y)\left(wh_{Ri}\right)^{1-\tau_y} di \tag{95}$$

$$\int \frac{y_i^{\tau_n}}{(1+a_n)} e_i di = \int \frac{e_i}{(1+\bar{a}_n)} di. \tag{96}$$

The government balances its budget every period:

$$\bar{a}_c \int c_i di + \bar{a}_y \int wh_{Ri} di = \frac{\bar{a}_n}{(1+\bar{a}_n)} \int p_i di + \bar{G}. \tag{97}$$

Solving for G. We start from the budget constraint of the agency that distributes research grants and use the guesses (25), (26) and $s_{eR} = G(k)e_R/R$:

$$\int G(k) \left[e_R + \int \mu_k(h) w_f(h) \right] dj + \bar{G} = \int \left[e_R + \int \mu_k(h) w_f(h) \right] dj$$

$$\iff \int (s_{eR} + s_{hR}) R(q) dj + \bar{G} = \int (s_{eR} + s_{hR}) R(q) G^{-1} k^{\tau_G} dj$$

$$\iff \int (s_{eR} + s_{hR}) e^{m_R - \frac{\chi_R}{\chi_k} m_k} k^{\chi_R/\chi_k} dj + \bar{G} = \int (s_{eR} + s_{hR}) e^{m_R - \frac{\chi_R}{\chi_k} m_k} k^{\chi_R/\chi_k} G^{-1} k^{\tau_G} dj$$

$$\iff (s_{eR} + s_{hR}) e^{m_R - \frac{\chi_R}{\chi_k} m_k} \int k^{\chi_R/\chi_k} dj + \bar{G} = (s_{eR} + s_{hR}) e^{m_R - \frac{\chi_R}{\chi_k} m_k} G^{-1} \int k^{\chi_R/\chi_k + \tau_G} dj$$

$$\iff (s_{eR} + s_{hR}) e^{m_R - \frac{\chi_R}{\chi_k} m_k} e^{\left(\frac{\chi_R}{\chi_k} m_k + \left(\frac{\chi_R}{\chi_k} \right)^2 \frac{\Sigma_k^2}{2} \right)} + \bar{G} =$$

$$(s_{eR} + s_{hR}) e^{m_R - \frac{\chi_R}{\chi_k} m_k} G^{-1} e^{\left(\left(\frac{\chi_R}{\chi_k} + \tau_G \right) m_k + \left(\frac{\chi_R}{\chi_k} + \tau_G \right)^2 \frac{\Sigma_k^2}{2} \right)}$$

$$G = \frac{(s_{eR} + s_{hR}) e^{m_R - \frac{\chi_R}{\chi_k} m_k} e^{\left(\left(\frac{\chi_R}{\chi_k} + \tau_G \right) m_k + \left(\frac{\chi_R}{\chi_k} + \tau_G \right)^2 \frac{\Sigma_k^2}{2} \right)}}{(s_{eR} + s_{hR}) e^{m_R - \frac{\chi_R}{\chi_k} m_k} e^{\left(\frac{\chi_R}{\chi_k} m_k + \left(\frac{\chi_R}{\chi_k} \right)^2 \frac{\Sigma_k^2}{2} \right)} + \bar{G}} = \frac{(s_{eR} + s_{hR}) e^{\tau_G m_k + \tau_G \left(2 \frac{\chi_R}{\chi_k} + \tau_G \right) \frac{\Sigma_k^2}{2}}}{(s_{eR} + s_{hR}) + e^{-m_R - \left(\frac{\chi_R}{\chi_k} \right)^2 \frac{\Sigma_k^2}{2}} \bar{G}}$$

where m_R in the last line is given by equation (75).

Finally, given that we target the ratio of research grants $\bar{G}$ over GDP $\bar{g} = \bar{G}/Y$, we get that G is given by

$$G = \frac{(s_{eR} + s_{hR}) e^{\tau_G m_k + \tau_G \left(2 \frac{\chi_R}{\chi_k} + \tau_G \right) \frac{\Sigma_k^2}{2}}}{(s_{eR} + s_{hR}) + e^{-m_R - \left(\frac{\chi_R}{\chi_k} \right)^2 \frac{\Sigma_k^2}{2}} \bar{g} Y}$$

$$\text{where} \quad Y_t = w_t \sum_{a=1}^{10} \exp \left(m_{h,t,a} + \frac{1}{2} \Sigma_{h,t,a}^2 \right)$$

Average income tax rate and intercept of income tax schedule If we target average income tax rate $\bar{a}_y$ then the following should be true

$$1-\bar{a}_y = \frac{\int (1-a_y)\,(wh_i)^{1-\tau_y}\,di}{\int wh_i di}$$
$$= \frac{(1-a_y)\,(w)^{1-\tau_y}\sum_{a=1}^{10}\exp\left((1-\tau_y)m_{h,t,a}+((1-\tau_y))^2\,\frac{\Sigma^2_{h,t,a,}}{2}\right)}{(w)\sum_{a=1}^{10}\exp\left(m_{h,t,a}+\frac{\Sigma^2_{h,t,a}}{2}\right)} \tag{98}$$

Average tuition subsidy and intercept of tuition subsidy schedule If we target the average subsidy to higher education $\bar{a}_n$, then the following should be true

$$1+\bar{a}_n = \frac{\int (1+a_n)e_i y_i^{-\tau_n}di}{\int e_i di} = \frac{\int (1+a_n)s y_i^{1-\tau_n}di}{\int s y_i di} = (1+a_n)(1-a_y)^{-\tau_n}\frac{\int (\tilde{w}h_i)^{(1-\tau_n)(1-\tau_y)}}{\int (\tilde{w}h_i)^{1-\tau_y}}$$
$$\iff 1+\bar{a}_n = \frac{(1+a_n)}{(1-a_y)^{\tau_n}}\frac{(\tilde{w})^{(1-\tau_y)(1-\tau_n)}\exp\left((1-\tau_y)(1-\tau_n)m_h+((1-\tau_y)(1-\tau_n))^2\,\frac{\Sigma_h^2}{2}\right)}{(\tilde{w})^{1-\tau_y}\exp\left((1-\tau_y)m_h+((1-\tau_y))^2\,\frac{\Sigma_h^2}{2}\right)}$$
$$\iff 1+\bar{a}_n = \frac{(1+a_n)}{(1-a_y)^{\tau_n}}\,(\tilde{w})^{-(1-\tau_y)\tau_n}\exp\left(-(1-\tau_y)\tau_n m_h+\tau_n(\tau_n-2)\,((1-\tau_y))^2\,\frac{\Sigma_h^2}{2}\right)$$
$$\iff a_n = (1-a_y)^{\tau_n}\,(\tilde{w})^{\tau_n(1-\tau_y)}\exp\left(\tau_n(1-\tau_y)m_h+\tau_n(2-\tau_n)((1-\tau_y))^2\frac{\Sigma_h^2}{2}\right)(1+\bar{a}_n)-1 \tag{99}$$

G Robustness Checks - Calibration Details

In this section, we conduct two robustness checks. The first one looks at the extreme case where the direct contribution of research to teaching quality becomes vanishingly small (e.g. $\omega_k \to 0$). This corresponds to a situation where intangible knowledge acts as a pure signal of the university's reputation and as a coordination device for high ability and wealthy students to congregate at the same colleges. Our second robustness check is motivated by the concern that some expenditures that are classified as "teaching expenses" are also inputs in research, such as buildings. These expenses could also contribute to the state variable k'. We thus propose a robustness check, where we generalize the production function of the dynamic input k' to incorporate some of the teaching equipment spending: $k' = k^{\gamma_k} e_R^{\gamma_e} \bar{h}_R^{\gamma_h} e_T^{\gamma_T}$.

In both robustness checks, we recalibrate all parameters. We calibrate the same set of moments as in the baseline calibration, with the exception of the innovation-education gap which we omit in the robustness check in which $\omega_k \to 0$. For the calibration of γ_T, we make the extreme and conservative assumption that teaching equipment is as productive for research as research equipment $\gamma_e = \gamma_T$. This is arguably an upper bound for γ_T, and the results should thus be interpreted as the most conservative of possible outcomes.