# A GENERAL EQUILIBRIUM ANALYSIS OF STATE AND PRIVATE COLLEGES AND ACCESS TO HIGHER EDUCATION IN THE U.S.

Dennis Epple[a]
[a]Carnegie Mellon University, Tepper School of Business, Pittsburgh, PA 15213, USA, and NBER
epple@cmu.edu

Richard Romano[b], *Corresponding Author*
[b]University of Florida, Department of Economics, Gainesville, FL 32611, USA
romanor@ufl.edu

Sinan Sarpça[c]
[c]Koç University, Department of Economics, Sariyer 34450, Istanbul, Turkey
ssarpca@ku.edu.tr

Holger Sieg[d]
[d]University of Pennsylvania, Department of Economics, Philadelphia, PA 19104, USA and NBER
holgers@econ.upenn.edu

Abstract. We develop a general equilibrium model of the market for undergraduate higher education that captures the coexistence of public and private colleges, the large degree of quality differentiation among them, and the tuition and admission policies that emerge from their competition for students. A quantitative version of the model matches well estimates of enrollment elasticities, variation in need-based and merit-based institutional aid with, respectively, student income and ability, and aggregate characteristics of U.S. higher education including college attendance in public and private schools, tuition levels, and the provision of federal aid. Predictions about the provision of federal aid and the distribution of students across colleges by ability and income match the empirical counterparts well. We use the model to examine the consequences of federal and state aid policies. A one-third increase in the maximum federal aid increases college attendance by 6 percent of the initial college population, most of the increase being in state colleges and mainly of poor students. Elite private colleges reduce institutional aid and use the net funding gain to spend more on educational inputs and to substitute some highly able poor students for less able rich students. Reductions in federal or state aid result in substantially reduced attendance mainly by poor students. Reductions of support to state colleges induces private colleges to increase enrollments modestly and improve in quality as demand shifts toward them.

KEYWORDS: College competition, college access, financial aid

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## 1. Introduction

Against a backdrop of an increasing gap in earnings between college and non-college graduates and persistently increasing costs of higher education, access to higher education has become a major policy concern. The Obama administration has passed and is advocating a variety of policies to increase access. Federal expenditure on Pell Grants, a means-tested and the most costly federal aid program for college students, increased from 14.7 billion dollars to 32.4 billion dollars between the years 2007-08 and 2012-13, and the number of grant recipients rose from 5.5 million to 8.9 million.[1] Tax credits for college expenses have been increased, the federal subsidized loan program has been reformed to increase college loans, and income-based repayment of loans has been expanded.[2] In addition, the Obama administration has proposed initiatives to keep down student costs, e.g., provision of more federal aid to colleges that keep down net tuition.[3] Understanding the impact of changes in programs of such magnitude requires an equilibrium model of the market for higher education. The purpose of this paper is to provide a general equilibrium analysis of access to colleges and to examine the effects of changes in funding policies on college attendance.

We develop a new model of the U.S. market for undergraduate higher education to provide a framework for understanding equilibrium choices of students and providers and to gain insights into the effectiveness of public policies. Building on recent advances in modeling the equilibrium in the higher education market, our model includes competing state and private colleges with alternative objectives, students that differ by income, ability, and unobserved idiosyncratic preference for colleges, and federal aid modeled to approximate U.S. policy. The model predicts college qualities, admission practices, and the college attendance pattern, including the characteristics of students that do not attend college. A quantitative version of the model does a good job of matching aggregates as well as estimates of enrollment elasticities and variation in need-based and merit-based aid with, respectively, student income and ability. The model also does a credible job predicting the provision of federal aid and the attendance pattern

[1] "The Federal Pell Grant Program," Congressional Budget Office Report, September 2013.
[2] https://www.whitehouse.gov/issues/education/higher-education.
[3] "FACT SHEET: President Obama's Blueprint for Keeping College Affordable and Within Reach for All Americans," press release, Office of the Press Secretary, The White House, January 27, 2012, https://www.whitehouse.gov/the-press-office.

of students that differ by income and ability. We employ the model to examine policy changes on attendance, with predictions in line with recent estimates. The analysis provides a more complete description of efficacy, with the potential to facilitate effective policy design.

One theoretical challenge is to capture the different objectives of private and public universities and the different constraints they face within a general equilibrium model. Our approach builds on the insight that neither public nor most private colleges are likely to maximize profit. Most private colleges focus primarily on their reputation. This motivates our approach of modeling private schools as maximizing quality, which depends on the measured abilities of their students and the educational resources colleges provide them.[4] We show that this leads private colleges to pursue a tuition and implied admission policy entailing merit aid to attract higher ability students and need-based aid to capture more revenues from higher-income students with stronger demands for college quality.

While private colleges are largely unconstrained in their policies, public universities face state mandates to provide affordable education to in-state students. This suggests modeling state universities as maximizing the aggregate achievement of in-state students. Public universities also face regulated price caps and have limited powers to set tuition and financial aid policies. However, they obtain direct subsidies from their state legislatures. Moreover, state regulated tuitions generally differ between in- and out-of-state students. With such a characterization of state colleges, our model shows that state colleges optimally use minimum ability admission thresholds that differ between in- and out-of-state students. Out-of-state students potentially provide two important functions for state schools. First, out-of-state students pay higher tuition rates and thus cross-subsidize the education of in-state-students. Second, they can provide valuable peer externalities since the admission standard for out-of-state students can be set higher than the admission standard for in-state-students. Our quantitative analysis suggests, however, the former force dominates leading to lower admission standards for out-of-state

[4] We focus on the higher education market served by four-year institutions in this analysis and do not consider for-profit colleges. Over 90 percent of the degrees conferred during 2000-2012 by for-profit institutions of higher education are associate degrees (17.3 percent) or certificates (74.1 percent), e.g., in hair dressing, massage, welding, and computer systems administration (Chakrabarti and Grisby, 2013). This raises the questions as to the extent to which for-profits compete for students with four-year institutions and whether they primarily serve a different demographic of students. While we have then not attempted to incorporate for-profit colleges into the analysis, such an extension is of interest, especially given their increasing role in higher education.

students.

A major goal of this paper is to evaluate the impact of public policies on access to higher education. In addition to state subsidies to public colleges, the federal government subsidizes higher education. Instead of providing higher education at subsidized rates, the federal government provides aid to students and their families that can be used at any college. The amount of available aid is basically determined by the difference between the cost of attending the college and the federally determined expected family contribution, as long as the difference is below a maximum amount of aid. The cost of attending includes the college's tuition, room and board, and an allowance for other expenses like books. Availability of federal aid increases qualifying students' demands to attend colleges. Faced with increased demand, private colleges might reduce institutional aid. Our analysis includes the equilibrium response of private colleges to provision of federal aid.

To assess the theoretical model and explore its quantitative implications, we develop a quantitative version of it. We calibrate the model using estimates of tuition effects on enrollment and variation in private college tuition with respect to student income and ability, and using important empirical aggregates including the proportion of students attending state versus private colleges and the proportion of college-aged individuals that attend college. In addition to matching well these values, the model predicts reasonably the distribution of federal aid and attendance patterns of students that differ by income and ability. After examining some variations in the model specification, we evaluate the effects of two policy changes. First, the Obama administration has significantly increased the amount of federal aid available to students. We show that a one-third increase in the maximum federal aid from $6,000 to $8,000 increases college enrollment by 6 percent, with those increases being primarily among relatively poor students and mainly at state institutions. Private schools react with a mixture of reduced institutional aid, increased expenditure on educational inputs, and by substituting some high-ability and lower-income students for some richer and less-able students. Average student costs among all public students falls by just $90, but the effects are very uneven depending on student characteristics. Some public school students save the entire $2,000. Effects in private colleges are very different because of their policy changes, including increased average tuitions. The policy change leads average private student costs to *rise*, though again effects are very uneven and poorer students experience a cost saving. We find that decreases in federal aid of the same magnitude have approximately the opposite effects.

The second policy experiment is motivated by the reduced state subsidies coupled with increased tuition that have occurred in a number of states on the heels of the recent recession. We examine a revenue neutral reduction in the per student state subsidy of $2,000 dollars accompanied by the same increase in tuition to in-state and out-of-state students. The share of the initial college population decreases by 9 percent. This enrollment decrease is entirely in state colleges, with mainly poor students exiting, but also with nontrivial exit of some upper-middle-income students who are too rich to qualify for federal aid. Increased federal aid protects some lower middle-income students from the state tuition increase who then remain in college. Demand shifts toward private colleges and they grow some. Elite private colleges substitute some higher-ability students of moderate income formerly at state institutions for some richer and lower-ability students.

A large literature exists on the economics of higher education. A general observation is that this literature has focused more on demand-side issues while taking as given college policies. We develop further the supply side of the market for higher education with our focus on college decision making and competition among colleges. By modelling college choices, we might better understand the quality variation across colleges, differences in tuition, admission and expenditure policies, variation in student bodies, and provide context to interpret and predict the effects of policy changes. A general equilibrium model is particularly useful to predict the effects of national policy changes on student attendance and costs. For example, the effects of a demand increase for higher education stemming from increases in federal grants on the tuition and admission policy of a college will depend on its market power and how competitors respond. A college monopolist will respond differently than would a college facing highly elastic demand due to close competitors. The market power of colleges will depend on differentiation among them. Concerted policy changes by Ivy League colleges would surely affect strategies of say Carnegie Mellon University and Rice, but not much say Gonzaga and the University of Georgia. Effects of changes in state college policies on college attendance are likely to depend on reactions of private colleges, with their reactions also relevant to their own students, as we find in our analysis. Policies that provide aid increases to the poorest students may impact state colleges more than private colleges, as we also find in our analysis. Designing national policies to promote attendance and to reduce student costs need to consider systemic effects. Our model is an attempt to advance the literature on the *market* for higher education.

This paper relates to the existing literature in several ways. First, a few theoretical papers focus on college pricing and admissions. Appealing to the example of higher education, Rothschild and White (1995) provide a model with peer effects and profit maximizing and competing private colleges. Type-specific prices exist such that free-entry equilibrium is efficient. Our model differs in a number of ways including colleges with alternative objective functions, market power of private colleges, and a multi-dimensional type space of students. Epple, Romano, and Sieg (2006) develop and estimate a model with competing private colleges that maximize quality.[5] The present model extensively generalizes that model by having a public sector of providers, unobserved idiosyncratic student preferences, and a realistic specification of provision of federal aid, all with fundamental consequences for the equilibrium allocation. Since roughly 70 percent of U.S. students in four-year colleges attend state colleges, including a public sector is necessary to obtain a more complete characterization of the market for higher education and to evaluate policy changes. The introduction of idiosyncratic preferences better explains provision of institutional financial aid by private colleges than in ERS (2006) and yields realistic attendance overlap of observationally equivalent students that does not arise there. The introduction of idiosyncratic preferences of students proves to be an important modeling advance in explaining the exercise of monopoly power of colleges that reconciles the widely observed price discrimination by income with the fact that no college serves more than a miniscule share of the student population. This modeling innovation also poses a substantial computational challenge, making solution of the model itself a valuable advance for research on higher education.[6] A realistic characterization of provision of federal aid is obviously needed to examine its effects on attendance.

Some research investigates college application choices of students when applying is costly and admissions are uncertain because students cannot predict how their applications will

[5] Building on Epple, Romano, and Sieg (2006), Sarpca (2010) studies specialization among colleges if students differ by a vector of skills.
[6] The computational methodology is discussed in an on-line appendix.

be assessed (see Chade, Lewis, and Smith, 2014 and Fu, 2014). In our model, though tuition and admission varies with observables, students know their options and an application-admission game does not arise. One interpretation of our model is that students apply to all the colleges to which their observable type is admitted as if application is costless. Another interpretation is that college tuition and admission policies are committed prior to application, in which case a student need only apply to the college they attend in equilibrium. Our simplification of the application stage facilitates analysis of a host of important features of the college marketplace: heterogeneity in students both with respect to ability and income, related price and admission discrimination by colleges, college expenditure choices, endogeneity in college qualities that effects demand and achievement, and alternative objectives between state and private colleges. Nonetheless, it is of much interest to merge our analysis with analysis where frictions imply uncertain admissions and an application-admission game. Such frictions might increase market power of colleges as costly applications reveal student preference for attendance, but the frictions themselves may limit college differentiation reducing market power.

Another strand of the theoretical literature on higher education concerned with admissions focuses on the effects of affirmative action policies [see Chan and Eyster (2003), Epple, Romano, and Sieg (2002, 2008), Loury, Fryer, and Yuret (2008), and Kapor (2015)]. The model here abstracts from race considerations. Finally, some other theoretical work has focused on the effects of early admission that are practiced by some elite colleges [see Avery and Levin (2010) and Kim (2010)], which we do not consider.

Our analysis makes predictions about the attendance pattern of heterogeneous students and about the effects on attendance of financial-aid policies. An empirical literature is focused on liquidity constraints faced by prospective students and consequences for college attendance. While there is an abundance of evidence that college attendance is correlated with household income, how much of this is explained by liquidity constraints versus preparedness is debated.[7] Our model provides micro-foundations for the relative roles of household income and student ability in predicting college attendance. We relate our model's predictions to the empirical

[7]See Cameron and Heckman (2001), Keane and Wolpin (2001), Carneiro and Heckman (2002), and Cameron and Taber (2004) for evidence that liquidity constraints are not the main barrier to college education. See Dynarski (2000, 2003), Stanley (2003), Kane (2007), and Cornwell, Mustard, and Sridhar (2006) for evidence that aid increases enrollments. Deming and Dynarski (2009) and Dynarski and Judith Scott-Clayton (2013) provide reviews of the evidence including many more references.

estimates of financial aid on attendance below. Recent empirical and experimental research has also investigated the role of information and complexity in students' applications for aid, college application, and attendance decisions.[8] We do not consider such informational problems.

The rest of the paper is organized as follows. Section 2 presents our equilibrium model of the market for higher education and relates general theoretical results. Section 3 develops the quantitative version of the model, demonstrates the model's match to empirical elements of college equilibrium, and examines some variations in the model. We examine policy changes in Section 4. Section 5 concludes. Some proofs are in the appendix.[9]

## 2. Private and Public Provision of Higher Education

We develop a new model of competition in higher education. Our specification incorporates both public and private sector provision of education, thereby modeling competition both within and across the public and private sectors. The model also assumes student preferences are private information, yielding new predictions with respect to who attends colleges. To clarify the basic mechanisms we abstract from the existence of the federal aid program in this section. In the next section, we augment the basic model with federal aid and some other elements. For expositional ease, we use "college," "university," and "school" interchangeably.

2.1. Higher Education Alternatives. We consider a model with S regions or states. Normalize the prospective student population in the economy to 1. Let $\pi_s$ denote the student population proportions or size of each state and note that $\sum_{s=1}^{S}\pi_s = 1$. Students in each state differ continuously by after-tax income $y$ and ability $b$. It is convenient to work with after-tax income, which is the relevant income to determine household choices. Let $f_s(b, y)$ denote the density of $(b, y)$ in state $s$. Each state operates one public university. In addition to the S public universities, there are $R$ private universities that operate nationwide. There is also an outside option referenced by 0 -- not attending university -- which is free and provides a given

[8] See Bettinger, Long, Oreopoulis, and Sanbonmatsu (2012) and Carrell and Sacerdote (2013) for experimental findings on the effects of providing information and financial assistance supporting college application, and for discussion of the larger literature.
[9] There is also an on-line appendix, the contents of which are noted as they arise in the paper.

educational achievement denoted by $a_0$. The total number of alternatives is then $J = S + R + 1$.[10]

The "student population" consists of the entire college-age population, including those that choose the outside option.

2.2. Preferences. A student with ability $b$ that attends a college of quality $q_j$ has an achievement denoted by $a(q_j, b)$. Let $p_{sj}(b, y)$ denote the tuition that a student from state $s$ with ability $b$ and income y pays for attending college j. Let $\varepsilon_j$ denote an idiosyncratic preference shock for school j, which is private information of the student.

**Assumption 1** *The utility of student (s,b,y) for college j is additively separable in the idiosyncratic component and given by:*

$$U_j(s,b,y,\varepsilon_j) = U(y - p_{sj}(b,y), a(q_j,b)) + \varepsilon_j. \tag{1}$$

$U(\cdot)$ *is an increasing, twice differentiable, and quasi-concave function of the numeraire and educational achievement,* $a(\cdot)$. *Educational achievement is an increasing, twice differentiable, and strictly quasi-concave function of college quality and own ability.*

Students choose among their college options to maximize utility as discussed further below. Let the optimal decision rule be denoted by $\delta(s,b,y,\varepsilon)$.

**Assumption 2** *The vector* $\varepsilon$ *satisfies standard regularity assumptions in McFadden (1974). Integrating out the idiosyncratic taste components yields conditional choice probabilities for each type:*

$$r_{sj}(b,y;P(s,b,y),Q) = \int 1\{\delta_j(s,b,y,\varepsilon)=1\}\, g(\varepsilon)\, d\varepsilon, \tag{2}$$

*where* $1\{\cdot\}$ *is an indicator function,* $\delta_j(\cdot)=1$ *means college j is chosen,* $P(s,b,y)$ *denotes the vector of tuitions that apply to student type (s,b,y), and Q denotes the vector of college qualities.*

2.3 Private Colleges. Private colleges attract students from all states of the country. Their objective is to maximize quality. We make the following assumptions about costs functions, private college endowments, and college quality.

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[10] We abuse notation for convenience by using $S$ to denote both the number of state colleges and the set of them $\{1, 2, \ldots, S\}$, and likewise for $R$ and $J$ (which usage will be obvious by context). Also for expositional convenience, we refer to university or college j from the set of all alternatives *J,* distinguishing the outside option 0 only when it is important to do so.

**Assumption 3** *College j has a cost function*

$$C(k_j, I_j) = F + V(k_j) + k_j I_j,\ V', V'' > 0, \tag{3}$$

*where* $k_j$ *denotes the size of college j's student body and* $I_j$ *denotes expenditure per student on educational resources in college j .*

The costs $F + V(k_j)$ are independent of educational quality, which we refer to as "custodial costs."

**Assumption 4** *Let* $E_j$ *denote the (exogenous) non-tuition income of college j. Private colleges can be ranked by these amounts:* $E_1 < E_2 < \ldots < E_R$.

**Assumption 5** *Letting* $\theta_j$ *denote mean ability in college j's student body, college quality* $q_j = q_j(\theta_j, I_j)$ *is a twice differentiable, increasing, and strictly quasi-concave function of* $(\theta_j, I_j)$.[11]

The model allows the college quality functions to differ. For example, private colleges might be more efficient than state colleges.

We model private colleges as monopolistically competitive:

**Assumption 6** *Private college j takes as given other colleges' tuitions and qualities when maximizing quality.*

Assumptions 3 and 5 apply to state colleges as well.

Under these assumptions, we can write the quality optimization problem of private college j as follows:

$$\max_{\theta_j, I_j, k_j, p_{sj}(b,y)} q_j(\theta_j, I_j) \tag{4}$$

subject to a budget constraint

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[11]There is a large literature on educational peer effects. Methodological issues in identifying peer effects are discussed in Manski (1993), Moffitt (2001), and Brock and Durlauf (2001). Recent research on peer effects in higher education includes studies of college dormitory roommates (Sacerdote, 2001; Zimmerman 2003; Boisjoly, Duncan, Kremer, Levy and Eccles, 2006; Duncan, Boisjoly, Kremer, and Levy, 2005; Stinebrickner and Stinebrickner 2006; Kremer and Levy, 2008), dormitory residential groupings (Foster 2006), randomly formed groups in military academies (Lyle, 2007, 2009; Carrell, Fullerton, and West, 2009), classroom peer effects (Arcidiacono, Foster, Goodpaster, and Kinsler, 2009), effects of high school peers (Betts and Morell,1999), and peer effects among medical students (Arcidiacono and Nicolson, 2005). See Epple and Romano (2011) for a more complete literature survey.

$$\iint\sum_{s=1}^{S}\pi_s\ p_{sj}(b,y)\,r_{sj}(b,y;P(s,b,y),Q)\,f_s(b,y)\,db\,dy+E_j\ =\ F+V(k_j)+k_jI_j \tag{5}$$

and identity constraints:

$$\theta_j\ =\frac{1}{k_j}\iint b\left(\sum_{s=1}^{S}\pi_s r_{sj}(b,y;P(s,b,y),Q)f_s(b,y)\right)db\,dy \tag{6}$$

$$k_j\ =\iint\left(\sum_{s=1}^{S}\pi_s r_{sj}(b,y;P(s,b,y),Q)f_s(b,y)\right)db\,dy. \tag{7}$$

Solving the private college's problem, we obtain the following result.

**Proposition 1** *For any student (s,b,y) with* $r_{sj}>0$, *tuition satisfies:*

$$p_{sj}(b,y)+\frac{r_{sj}(b,y;\cdot)}{\partial r_{sj}(b,y;\cdot)/\partial p_{sj}(b,y)}\ =\ V'(k_j)+I_j+\frac{\partial q_j(\theta_j,I_j)/\partial\theta}{\partial q_j(\theta_j,I_j)/\partial I}(\theta_j-b). \tag{8}$$

The proof is in the appendix.[12]

The left-hand side of (8) is marginal revenue, reflecting the college's exercise of market power to extract rents from those who have a strong idiosyncratic preference for the college. The right-hand side is the "effective marginal cost" of student *(s,b,y)*'s attendance, which sums the marginal resource cost given by the first two terms and the marginal peer cost given by the last term. The marginal peer cost multiplies the negative of the student's effect on the peer measure (equal to $(\theta-b)/k$) by the resource cost of maintaining quality (equal to $\frac{\partial q/\partial\theta}{\partial q/\partial I}k$). Henceforth, we let:

$$EMC_j(b)\equiv V'(k_j)+I_j+\frac{\partial q_j/\partial\theta}{\partial q_j/\partial I}(\theta_j-b)$$

(9)

denote the effective marginal cost of the student. Note that EMC varies with students in college j only with the student's ability, and that the peer cost is negative for students of ability exceeding the school's mean.[13] $EMC_j(\cdot)$ also depends on $(k_j,I_j,\theta_j)$, but we suppress this to simplify

[12] Epple, Romano, and Sieg (2006) characterize optimal private college pricing in a model with no informational asymmetry; colleges then charge each admitted student his or her reservation price (i.e., practice first-degree price discrimination) and admit only those with reservation price that covers their *EMC*. Significant need-based institutional aid arises in such a full-information setting only if colleges are assumed to have a preference for income diversity in the student body. Here we obtain substantial need-based aid without such an assumption.

[13] It is interesting to compare this result to that for a profit-maximizing private college. We have shown a profit-

notation. For $V''$ sufficiently high, *EMC* will increase with $k_j$, which we assume holds. Students for whom marginal revenue is below *EMC* at $k_j$ with $r_{sj} = 0$ are not admitted to college j.[14] Let $R_a(s,b,y)$ denote the subset of private colleges that admit *(s,b,y)* types.

2.4 Public Colleges. From the perspective of a state college a student is either an in-state student or an out-of-state student. We assume that the state legislature sets tuition rates and the per student subsidy, and we do not model this process.[15]

**Assumption 7** *Tuition charged to in-state students is fixed exogenously at* $T_s$ *and to out-of-state students at* $T_{so}$. *The state also provides its college an exogenous per student subsidy of* $z_s$, *financed by a balanced budget state income tax denoted* $t_s$.

Keep in mind that household income y is after-tax income, thus adjusted for variation in tax rates when we examine policy changes. We assume a state college maximizes the aggregate achievement of its in-state students. This can also be interpreted as an objective of maximizing future income of in-state students.

**Assumption 8** *Letting* $\gamma_s(b,y) \in [0,1]$ *denote the fraction of in-state students of type* $(b,y)$ *state college s admits and* $r_{ss}(b,y)$ *the fraction of those admitted that attend, the state college maximizes:* $\int\int a(q_s(\theta_s, I_s), b)\gamma_s(b,y) r_{ss}(b,y;P,Q) f_s(b,y) dbdy.$

To write a state college's optimization problem while taking account of the constraints, let

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maximizing college would have a tuition function that is of the exact *form* of (8). Given educational inputs, the quality maximizing college sets tuition to maximize profits, while taking account of the peer value effect, so as to have the maximum funds to increase quality. However, the quality maximizing college has stronger incentive to spend on educational inputs, implying the expenditure on inputs will differ between the profit and quality maximizers. Moreover, the latter implies the weight on the peer effect $(\theta - b)$ in (8) will differ, likely implying the quality maximizer has stronger incentives to attract higher ability students. Distinguishing the objectives empirically is then relatively subtle, as both objectives imply similar pricing, though merit aid should be steeper under quality maximization. Quality maximization also leads to use of revenues to enhance educational resources beyond their effects on increasing revenues.

[14] Colleges might face absolute capacity constraints especially in the short run. Suppose that $k_j \le k_j^c$ is a binding capacity constraint. As shown in the appendix, a college would then set tuition to admitted students so that marginal revenue (MR) minus EMC equals a positive constant, EMC evaluated at $k_j = k_j^c$; and with $\iint \sum_{s=1}^{S} \pi_s r_{sj} f_s dbdy = k_j^c$. The college would fill its capacity with student types for whom the excess of marginal revenue over effective marginal cost is the highest. The college would not admit any student types for whom the difference between MR and their EMC evaluated with none admitted is below that of admitted students.

[15] The key challenge in making endogenous tuition rates and college subsidies in public colleges is to model decision making by state legislatures. These policies are likely to vary with the political party in power in the state. While it is of interest to extend the analysis to have endogenous public tuition and subsidies, we have left this as a topic for future research.

$\gamma_{so}(b,y)\in[0,1]$ denote the proportion of out-of-state students of type *(b,y)* the college admits and $r_{ts}(b,y;P,Q)$ the fraction of those admitted from state $t\neq s$ that attend.[16] State college $s$ solves:

$$\max_{\theta_s,I_s,k_s,\gamma_s(b,y),\gamma_{so}(b,y)} \iint a(q_s(\theta_s,I_s),b)\gamma_s(b,y)r_{ss}(b,y;P,Q)f_s(b,y)dbdy \tag{10}$$

subject to the identity constraints:

$$\begin{aligned}\theta_s &= \frac{1}{k_s}\int\int b\pi_s\gamma_s(b,y)r_{ss}(b,y;P,Q)f_s(b,y)dbdy \\ &+\frac{1}{k_s}\int\int b\gamma_{so}(b,y)\left(\sum_{t\neq s}\pi_t r_{ts}(b,y;P,Q)f_t(b,y)\right)dbdy\end{aligned} \tag{11}$$

and

$$\begin{aligned}k_s &= \int\int \pi_s\gamma_s(b,y)r_{ss}(b,y;P,Q)f_s(b,y)dbdy \\ &+\int\int\gamma_{so}(b,y)\left(\sum_{t\neq s}\pi_t r_{ts}(b,y;P,Q)f_t(b,y)\right)dbdy\end{aligned} \tag{12}$$

the budget constraint:

$$\begin{aligned}F+V(k_s)+k_sI_s-z_sk_s &= \int\int p_{ss}(b,y)\pi_s\gamma_s(b,y)r_{ss}(b,y;P,Q)f_s(b,y)dbdy \\ &+\int\int\gamma_{so}(b,y)\left(\sum_{t\neq s}\pi_t p_{ts}(b,y)r_{ts}(b,y;P,Q)f_t(b,y)\right)dbdy\end{aligned} \tag{13}$$

the tuition regulation constraint:

$$p_{ts}(b,y) = \begin{cases} T_s \text{ for all students } (t,b,y) \text{ with } t=s \\ T_{so} \text{ for all students } (t,b,y) \text{ with } t\neq s \end{cases} \tag{14}$$

and the feasibility constraints:

$$\gamma_s(b,y),\gamma_{so}(b,y)\in[0,1] \text{ for all students } (t,b,y) \tag{15}$$

The following result summarizes optimal policy of state colleges (with proof in the appendix):

[16]The value to college s of attracting an out-of-state student of type (b,y) does not vary with the state, implying it is optimal to admit out-of-state students of type (b,y) with the same frequency. The yield will vary in general, however.

**Proposition 2** *State college s admits all in-state students with* $b \geq b^{s}_{\min}$, *all out-of-state students with* $b \geq b^{o}_{\min}$, *and no other students, where*

$$a(q_s(\theta_s, I_s), b^{s}_{\min}) / \lambda + T_s + z_s - EMC_s(b^{s}_{\min}) = 0 \qquad (16)$$

$$T_{so} + z_s - EMC_s(b^{o}_{\min}) = 0 \qquad (17)$$

*and λ is the multiplier on the budget constraint. Since $EMC_s(b)$ is a decreasing function, it is further implied that:*

$$b^{s}_{\min} < (=)\ (>)\ b^{o}_{\min} \ \text{as} \ a(q_s(\theta_s, I_s), b^{s}_{\min}) / \lambda + T_s > (=)\ (<)\ T_{so}. \qquad (18)$$

Out-of-state students are admitted if and only if the revenue they generate covers their $EMC_s(b)$. Their relative value to the state school comes from their tuition and, perhaps, positive effect on in-state peers. In-state students have an additional marginal value of attendance, specifically their direct contribution to the school's objective of in-state achievement maximization. The term $a / \lambda$ in (16) and (18) equals the monetized value of the increase in aggregate state achievement from the in-state student's attendance. While $T_s < T_{so}$ empirically, it could be that $a(q_s(\theta_s, I_s), b^{s}_{\min}) / \lambda + T_s > T_{so}$, implying a lower admission standard for in-state students.[17]

2.5 Utility Maximization. Let $S_a(s,b,y)$ denote the subset of state colleges to which student *(s,b,y)* is admitted, and $J_a(s,b,y) \subset S_a(s,b,y) \cup R_a(s,b,y) \cup O$ the options that provide positive utility to the student. Taking as given tuitions, qualities, and federal aid (introduced later), student *(s,b,y)* chooses among $j \in J_a(s,b,y)$ to maximize utility. By Assumption 2, the choice $\delta(s,b,y,\varepsilon)$ is generically unique, with choice probabilities for student type *(s,b,y)* given by (2). In our model, though tuition and admission varies with observables, students know their options and an application-admission game does not arise. One interpretation of our model is that students apply to all the colleges to which their observable type is admitted as if application

[17] As for private colleges (see footnote 14), there could be binding capacity constraints on admissions. Then (16) and (17) are modified to have the RHS the same positive value. The result in (18) is unchanged, but higher ability admission thresholds would arise to meet the capacity constraint.

is costless. Another interpretation is that college tuition and admission policies are committed prior to application, in which case a student need only apply to the college they attend in equilibrium.[18]

2.6 State Budget Balance. To close the model, we assume that each state operates with a balanced budget. Letting $Y_s$ denote aggregate pre-tax income in state *s* per potential college student in the economy, the state income tax satisfies:

$$t_s Y_s = z_s k_s \text{ for all } s \in S. \tag{19}$$

2.7 Definition of Equilibrium. We are now in a position to define equilibrium formally. Let $P_{-j}$ denote the vector of price functions that omits college j, and likewise for qualities $Q_{-j}$. The exogenous elements of equilibrium are: (i) the student utility and achievement functions and the distribution on the idiosyncratic preference vector; (ii) the state student type distributions and proportions; (iii) the college cost and quality functions; (iv) the number of private colleges and their non-tuition revenues; (v) the number of states, their state subsidies, and in- and out-of-state tuitions; and (vi) achievement if the outside option is chosen.

**Definition 1** *Given (i) - (vi), an equilibrium consists of a price and quality vector* $(P, Q)$ *with corresponding college characteristics* $(\theta_j, I_j, k_j)$ *for all* $j \in J \setminus O$; *state admission criteria* $(\gamma_s(b,y), \gamma_{so}(b,y))$ *for all* $s \in S$; *and a set of student choices* $\delta(s,b,y,\varepsilon)$ *for all* $(s,b,y)$ *and* $j \in J$ *with corresponding utilities* $U_j$ *and choice probabilities* $r_{sj}(b,y)$ *that satisfy:*

*(a) private college quality maximization by all colleges* $j \in R$, *taking as given* $(P_{-j}, Q_{-j})$, *the student choice probability functions, and public policies;*

*(b) public college in-state achievement maximization by all state colleges* $s \in S$, *taking as given* $(P_{-s}, Q_{-s})$, *the student choice probability functions, and public policies;*

*(c) utility maximization by all students* $(s,b,y)$, *taking as given* $(P, Q)$ *and public policies*

[18] In Chade, Lewis, and Smith (2011) and Fu (2012) students face application costs and are uncertain about their admission to colleges due to uncertainty about how their credentials will be evaluated. Then an application-admission game arises. It is of interest to build such frictions into a model with price discrimination by colleges. We also abstract from the choice of a major. Arcidiacono (2005) and Bordon and Fu (2012) develop and estimate a dynamic model of choice of academic major under uncertainty.

*including state admission criteria; and*

*(d) balanced state budgets.*

The equilibrium notion is monopolistically competitive. In particular, colleges take as given other colleges' prices and qualities when choosing their own policies. Thus, a college does not consider that variation in their own pricing/admission policies will have an impact on other colleges' qualities through size and peer effects. This is reasonable if individual colleges are small in the market for students and vastly simplifies the analysis.

2.8 Equilibrium Selection. Multiple equilibria might arise due to the peer effect on college quality. We restrict attention to a "hierarchical adherence" equilibrium that requires the private college hierarchy to follow the endowment hierarchy, with state colleges of lowest quality. This might be violated, for example, if the quality-taking students expect a higher-ability peer group and thus higher quality at a college with lower endowment; and the implied student demands lead quality maximizing qualities to set tuition, admissions, and expenditures consistent with these student expectations. Facing low demands, a higher endowed college may find it difficult to attract high ability students and offset this with generous institutional aid and/or high per student expenditure. Given we must select an equilibrium to perform policy analysis, we analyze what is arguably the most natural equilibrium.[19] We compute equilibrium below in non-trivial cases, demonstrating equilibrium can exist.

2.9 Federal Aid, Price Caps, and Non-Tuition Costs For clarity, we have thus far focused on the model without federal financial aid. In this sub-section, we introduce a realistic approximation of financial aid into the model specification. To obtain a better quantitative model, it is also desirable to account for price caps in private schools and non-tuition student costs. We discuss each of these extensions here.

[19] Equilibrium would need to satisfy hierarchical adherence if state colleges have low subsidies and if private college endowments are sufficiently different since student quality expectations must be consistent with the college quality choices that actually arise. However, it is doubtful the theoretical condition holds in reality and there appear to be exceptions in reality (e.g., Franklin W. Ohlin College of Engineering is ranked among the top five in per student endowment, but their ranking in engineering, while high, is not comparable). In defense of the assumption as an approximation, the components of college quality are highly correlated with per student endowment. For their sample of 1,241 nonprofit, four-year public and private colleges, Epple, Romano, and Sieg (2003) report a correlation between per student endowment and per student expenditure of .80 and between per student endowment and mean SAT equal to .34.

Though we do not have an explicit theory explaining a private college's "list tuition" or "price cap," in practice private colleges adopt a tuition maximum and then provide some students with financial aid.[20] Let $P_j^c$ denote private college j's price maximum or cap, which we treat as exogenous. Institutional aid to student $(s,b,y)$ is then given by $P_j^c - p_{sj}(b,y)$.

The federal government provides college students with aid through several programs. Broadly speaking, federal aid levels vary with student resources and with the cost of attending college. For students seeking aid, the federal government first computes a student's expected family contribution (*EFC*). This is the amount the federal government deems as appropriate for the family to pay out-of-pocket for a college education. In addition to the student's family income, this depends on a variety of factors, most importantly family assets and family size. As described in more detail below, we can model *EFC* as an increasing function of the student's after-tax family income. Federal aid is then linked to the difference between the student's cost of attendance (*COA*), as calculated by college j, and the student's *EFC*. The idea is that aid should be made available only to the extent the student's educational costs exceed *EFC*. The *COA* equals list tuition (including mandatory fees) plus an allowance for non-tuition costs, mainly for room and board, books, and travel expenses.[21] We assume the allowance (*L*) is the same at all colleges so that $COA_j = P_j^c + L.$ Federal aid programs generally have a maximum award, which we denote in total by $\overline{A}.$ A student's federal aid at private college j is then given by:

$$A_j(y) = Min\{Max[0, P_j^c + L - EFC(y)], \overline{A}\}. \qquad (20)$$

Federal aid at state colleges is calculated analogously, with the list price of private schools replaced by the in- or out-of-state tuition. Thus, in state colleges, federal aid generally varies for in- and out-of-state students, so we write aid as $A_{sj}(y)$ to account for cases where the college is public.

To investigate the effects on equilibrium, first note that the attendance probabilities are adjusted for federal aid and the non-tuition costs:

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[20]Adoption of a price maximum is probably explained by marketing to students and society. Below we examine the effect of removing the price cap on the most elite private college.

[21] "List tuition" in state colleges is the relevant state-set tuition. We include mandatory fees in the list tuitions.

$$r_{sj} = r_{sj}(b, y - L + A_{sj}(y); P(s,b,y), Q). \tag{21}$$

The state college problem is as above with the adjustment to the attendance probabilities, and the admission criterion continues to satisfy Proposition 2.

Adoption of a price cap modifies the solution to a private college's problem in a straightforward way. Proposition 3 summarizes the effects of price caps, non-tuition costs, and federal aid on pricing and admissions of a private college. To state and understand Proposition 3, we must take account of the fact that $EMC_j(\cdot)$ is a function of $k_j$, which is itself a function of the proportion of a type attending college. Here we then write $EMC_j(b, k_j(r))$, where r denotes the proportion of the type of interest. Define $\hat{r}_j(b)$ in $EMC_j(b, k_j(\hat{r})) = P_j^c$, this proportion illustrated in Figure 1.

**Proposition 3** *No students for whom* $EMC_j(b, k_j(0)) \geq P_j^c$ are admitted to private college j. For students for whom $EMC_j(b, k_j(0)) < P_j^c$ :

$$\begin{aligned} p_{sj}(b, y - L + A_{sj}(y)) + \frac{r_{sj}(b, y - L + A_{sj}(y), \cdot)}{\partial r_{sj}(b, y - L + A_{sj}(y), \cdot) / \partial p_{sj}(b, y - L + A_{sj}(y))} \\ = V'(k_j) + I_j + \frac{\partial q_j(\theta_j, I_j)/\partial \theta}{\partial q_j(\theta_j, I_j)/\partial I}(\theta_j - b). \end{aligned} \tag{22}$$

*and* $r_{sj}$ *satisfies (21) if* $p_{sj} \leq P_j^c$;

$$\begin{aligned} &p_{sj} = P_j^c \text{ if } p \text{ satisfying (22) exceeds } P_j^c, \\ &\text{and} \begin{cases} r_{sj} \text{ satisfies (21) if } r_{sj} > \hat{r}_j(b) \\ r_{sj} = \hat{r}_j(b) \text{ otherwise.} \end{cases} \end{aligned} \tag{23}$$

**Proof of Proposition 3** Note that the RHS of (22) is *EMC* as defined in (9). Refer to Figure 1, which shows the demand of a type to attend college j in the presence of a price cap (labeled $D_{sj}$), the implied marginal revenue (labeled $MR_{sj}$), and four cases of *EMC*.[22] For the lowest *EMC*, $EMC_1$, the price cap is non-binding and quality-maximizing pricing is unconstrained. Here, by analogy to pricing in (8), tuition satisfies (22), which adjusts income for non-tuition costs and

[22] Demand that is unconstrained by the price cap is given by the choice probability multiplied by the density of the type.

any federal aid; and attendance is on demand.[23] For $EMC_2$, the price cap is binding and the optimum is at a corner solution with tuition equal to the price cap. It would not be optimal to reduce admissions below demand since the effective marginal revenue (equal to the price cap) exceeds effective marginal cost. For $EMC_3$, tuition equal to the price cap is obviously optimal, but restricting admissions below the level of demand is also (obviously) optimal. The latter two cases conform to the respective cases in (23). For $EMC_4$, admitting any students would reduce quality, completing the proof.

To close the model we assume a proportional income tax is imposed on all households (in addition to the state tax) to finance federal aid. The definition of equilibrium is modified in a simple way.

## 3 Quantitative Model and Analysis

3.1 Quantitative Model Specification. To assess the performance of the model, we examine a numerical specification of it and then compute equilibria under alternative public policies.[24] First, we specify the forms of the quality, achievement, and utility functions.

**Assumption 9** *The college quality function is given by*

$$q_j = \delta_j \theta_j^{\gamma} I_j^{\omega}, \ \ \delta_j, \gamma, \omega \ > \ 0, \tag{24}$$

*and achievement if college j is attended is given by*

$$a_j = q_j b^{\beta}, \ \beta > 0. \tag{25}$$

*The utility function for college j or the outside option ( j = 0):*

$$U_j(y - L + A_{sj}(y) - p_{sj}, a_j)) = \alpha \ln[(y - L + A_{sj}(y) - p_{sj})a_j] + \varepsilon_j \tag{26}$$

*with $\alpha$ a weighting parameter. The disturbances $\varepsilon_j$ are independent and identically distributed with Type I Extreme Value Distribution having location parameter equal to zero and scale parameter equal to one.*

3.2 Calibration and the Baseline Equilibrium. We must calibrate the number of colleges, public policies applying to state colleges, the price caps and endowments of private colleges, the college cost function, the joint income and ability distribution of the potential student population, the

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[23] Note that federal aid to a student at private college j is not influenced by $p_{sj}$, rather depends on the list price at college j. If, instead of using the list price to determine the student's *COA*, the student's price adjusted for institutional aid were used, this would lead to extreme gaming by private colleges. We characterized this in an earlier version of the paper. In reality, list prices are used in determination of aid.

[24] The on-line appendix discusses how to compute equilibria.

federal aid formula, non-tuition costs, and the parameters of the utility and college quality functions. Much of this can be "directly" calibrated, meaning empirical values are observed that permit direct estimation as for the income distribution of prospective students. One cannot, however, use such an approach in calibrating the parameters of the utility and college quality functions. The basic strategy here is to use predictions of the model about elasticities and aggregates characterizing the equilibrium to approximate empirical counterparts, as described in detail below. The model fit to values used in calibration serves as some validation itself, but we also present evidence of accuracy of other predictions of the model.

Table 1 summarizes the parameter values that we use.[25] Our calibration is based on the 2007-08 academic year. We consider a model with two states, each having one state school, and with the same state policies and distributions of potential student types. We need at least two states to examine issues regarding in- and out-of-state students, and we assume just two for simplicity. The average in-state tuition in 2007-08 was $6,200, and the average out-of-state tuition was $15,100 for full-time undergraduates enrolled in public 4-year institutions. The average public subsidy was $8,495 per Full Time Equivalent (FTE) student.

We assume three private colleges to allow non-trivial variation in college qualities, yet maintain tractability. To obtain values for private colleges, we rank colleges by SAT score and combine them into three groups. Endowments per student are chosen to correspond to those in the NSF WebCASPAR data. An assumed 2 percent annual draw allocated to undergraduate education yields the per student endowment values in Table 1. Average list prices for private bachelor's and private research universities in 2009 were 22.6 and 30.4 (in thousands of dollars henceforth). These values guide our choice of price caps that ascend across the quality hierarchy as shown in Table 1.

As also reported in Table 1, the parameters of the utility-quality functions in (24) and (25) are set at $\alpha = 20$, $\gamma = .15$, $\omega = .155$, and $\beta = .80$. We normalize the college efficiency parameter $\delta_j$ to equal 1 in public colleges, and set $\delta_j = 1.0525$ in each private college. Achievement in the outside option is set to $a_0 = 2.0267$. These 6 parameters are chosen so that the equilibrium approximates key aggregate characteristics of U.S. higher education and

[25]The on-line appendix details sources used in the calibration and provides more detail.

estimates of the effect of institutional aid on enrollment and variation in institutional aid with student income and ability. Refer to the first two columns of Table 3. Specifically, we target these empirical values: (i) the average private tuition net of institutional aid equal to $23,400; (ii) the student percentage of private schools in total enrollment equal to 30; (iii) total college enrollment as a percentage of the potential student population equal to 40; (iv) the percentage of in-state students attending state colleges equal to 90; (v) van der Klauuw's (2002) estimates of the enrollment elasticity of institutional aid of .70; and (vi) our estimates of need-base and merit aid as they vary respectively with student income and ability.[26] While all 6 parameters jointly determine the model's predictions corresponding to the latter values, one can narrow their identification to some degree. The largest effect of varying $a_0$ is on the proportion that attend any college. The value of $\beta$ also impacts significantly the proportion that attends college, because higher $\beta$ increases the payoff to ability in college. Both $a_0$ and $\beta$ are important in determining the enrollment elasticity. The value of $\alpha$ is most important in determining the proportion of in-state students, which is relatively sensitive to the weight on the non-idiosyncratic part of utility. Not surprisingly, the relative quality parameter $\delta_j$ on private schools is important in predicting the relative proportion that attend private schools. The values of $\omega$ and $\gamma$ are, respectively, mainly identified by the estimates of income and need-based aid in private schools, and these then also have significant impact on average tuition (or average institutional aid) in private colleges.

We also set the non-tuition cost of attending college (room and board, travel, supplies), L, to $10,250, this "directly" calibrated as detailed in the on-line appendix.

We specify the college cost function as $C(k,I)= F + v_1 k + v_2 k^2 + kI$. Epple, Romano, and Sieg (2006) estimate "custodial cost functions" (costs net of $kI$) using micro data for a large sample of colleges and discuss how to aggregate cost functions. Their analysis suggests that average cost functions initially decline quickly and then are fairly flat over a large range of values. Also, custodial costs amount to approximately 60 percent of total expenditures on average.[27] Given the values of utility function parameters and the number of state and private

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[26] These estimates we target are taken from Epple, Sarpca, Sieg,, Romano, and Zaber (2016). See especially Table 5 and the accompanying discussion.
[27] See Table 1 in Epple, Romano, and Sieg (2006).

schools, the cost function parameters also need to be consistent with school sizes in equilibrium. Based on these considerations, we specify the cost function parameters in Table 1.

To approximate the *EFC* function, we assume that the student is a dependent, is the only college student in a household with 3 or 4 family members, and follow the *EFC* formula guide Worksheet A.[28] *EFC* is weakly increasing in after-tax income and non-excluded assets, with various allowances. We set a student's income equal to zero and assume the household head is of age 45 to 54. Using our assumptions about family characteristics, we calibrate the household's relevant assets and the several allowances in the *EFC* formula. While the empirical *EFC* function is piecewise linear with 7 adjusted income tiers, we approximate it with a three tier function of after-tax income: $EFC(y) = \max\{0, .48y - 10{,}300, .69y - 22{,}500\}$. This implies, for example, that a student with *COA* (list tuition plus $10,250) equal to $40,000 loses eligibility for any federal aid as after-tax income rises above $90,580.

We measure federal aid as a weighted sum of grants, work-study aid, and loans using the formula: Federal Aid = Grants + 0.33 Work-study + 0.1 Loan. The maximum Pell Grant in 2008 was $4,731. Subsidized federal loans are capped at $3,500 and $4,500 for the first two years, and at $5,500 for each year after that. The upper limit on work-study earnings varies by the cost of living, with the average is on the order of $2,500. Combining these and weighting according to the above formula implies a maximum federal aid of very close to the $6,000 we assume here.

We use data from the Current Population Survey (CPS) for 2009 to estimate the after-tax income distribution. We find that a lognormal distribution with a location parameter (standard errors shown in Table 2) fits the data well $\ln(y + 41{,}536) \sim N(11.46, .402)$. Ability is calibrated assuming a lognormal distribution, normalized such that $\ln(b) \sim N(1.0, 0.15)$, matching the distribution of IQ. We follow Epple and Romano (1998, 2008) in setting the correlation of household income and student ability as 0.4.

The first two columns of Table 3 summarize the fit of our baseline model. We match well the values used in the calibration, though over-predict some the proportion of in-state students that attend their state's public college. An extension of the model that might resolve this would be to introduce foreign students, which we leave as a topic for future research. Regarding values not used in the calibration, the model does a good job of predicting federal aid in state and

[28]This is available at https://studentaid.ed.gov/. The on-line appendix describes our calibration of EFC in detail.

private colleges and the proportions that receive aid, though under-predicting these a bit. While not perfect, overall the model does an excellent job of replicating empirical values.

Panel A of Table 4 provides more detail on the baseline equilibrium.[29] Values by college are shown, with the first two rows for the two identical state colleges and the next three rows for the three private schools ordered by their quality and thus per student endowment. The state colleges are much larger ($k_j$) than the private colleges and private college sizes are inversely related to their qualities. Mean student ability, resources per student, average tuition, and the mean income of students all increase along the college quality hierarchy. Average federal financial aid is higher in private than state colleges. Average federal aid declines with private school quality in spite of higher tuition, this because wealthier students attend the higher quality colleges with fewer obtaining federal aid. The last column reports the proportion paying full tuition in each private college and thus receiving no institutional aid. The attendance-weighted average percentage paying full tuition from the model is 39 percent, not far from the NCES estimate of 33 percent in private nonprofit 4-year colleges.[30]

The minimum ability thresholds for admission at state schools are low, with state schools admitting virtually all out-of-state students. Thus, the higher tuition that state colleges get from out-of-state students dominates their being weaker peers on average (as discussed in Proposition 2).

More detail about attendance distributions is provided in the panels of Table 5, which show the percentages of prospective students attending the described college or set of colleges by income and ability deciles. For example, in the middle panel titled "all private colleges," the entry in the upper right cell means that 67 percent of prospective students in the highest income and ability deciles attend a private college in equilibrium. The top two panels, for the top private college and all private colleges respectively, illustrate both the selectivity of private colleges and the relative greater selectivity of the most elite private college.[31] The lower panel illustrates that public colleges tend to attract proportionally more middle-income and less-rich students in the

[29] Each state has an income tax of 3.9 percent to finance the state subsidies and the federal income tax rate that finances federal aid is .9 percent.
[30] See Figure 3, "Student Financing of Undergraduate Education: 2007-08: Sticker, Net, and Out-of-Pocket Prices," August 2010, Institute of Education Sciences, National Center for Education Statistics.
[31] This information for all colleges is available in the on-line appendix.

middle of the ability distribution.[32] No poor and low-ability students attend college, and almost all high-ability students with median or higher income attend some college. While equilibrium has a degree of income and ability stratification across the college quality hierarchy, one can see in Table 5 that many students with the same ability and income attend different colleges. For example, 33 percent of students in the highest income and ability decile attend state colleges, with the rest distributed across the private colleges. This attendance overlap is in contrast to Epple, Romano, and Sieg (2006) where pure income and ability stratification arises, the underlying difference being idiosyncratic variation in student preferences for colleges here. The empirical overlap in attendance is obvious, lending support to the alternative preference and information specification adopted here.

Differences in attendance between state and private colleges, and across the private college hierarchy, are explained by the differences in objectives of the two types of colleges, the differences in the constraints they face, differences in endowments across the private colleges, and competition among colleges.[33] State colleges are much larger and serve many more lower-ability students, especially poorer ones, in part reflecting their objective to maximize aggregate achievement of their in-state residents. Private colleges are more elite given their objective of maximizing quality. They have higher ability and richer students, the latter helping to finance their higher expenditure. Private colleges with higher endowments are relatively more elite than those with lower endowments, as they can spend more on educational inputs to increase quality and offer steeper discounts to poorer very desirable (very high ability) students to attract them.[34]

3.3 Predicted and Empirical Attendance Patterns. We saw in Table 3 that our baseline model matches the 2007-08 data quite well, including variables not used in calibration. A further test of the model is to compare predicted and actual attendance patterns by income and SAT. The 2007-

[32] Beginning at the highest income, for given ability, as income declines the proportion attending private schools drops, with then a greater proportion instead attending less expensive state colleges. But then proportional attendance jumps up at private colleges as income drops around the 70th income percentile (among students of sufficient ability). This occurs because students become eligible for substantial federal financial aid and private schools provide some institutional aid.

[33] As discussed in Section 2.8, we have also selected equilibrium with the quality hierarchy following the endowment hierarchy.

[34] From (8), the marginal value of ability in private college j equals $\frac{\partial q_j / \partial \theta}{\partial q_j / \partial I}$, which equals $\gamma I_j / \omega \theta_j$ in the quantitative model. This marginal value increases with college quality in equilibrium.

08 NPSAS does not provide the income detail required for such an analysis, but the 2011-12 NPSAS does provide the requisite detail. The 2011-12 academic year follows a period of marked increase in federal financial aid, an increase of roughly 120% from 2007-08 to 2010-11.[35] Hence, we compute equilibrium of our model with the increased federal financial aid. We then compare the resulting predictions to the outcomes observed in the 2011-12 data. This is akin to an out-of-sample test of the model. It is a relatively demanding test as it entails not only a detailed comparison by income and SAT, but also a comparison of equilibrium outcomes calculated to incorporate the large increase in financial aid that occurred relative to our baseline calibrated to 2007-08. In particular, to investigate predictive accuracy, we computed equilibrium in our model with an increase in maximum federal aid from $6,000 to $9,000.[36] This yields an equilibrium increase in aid of 125%, an increase closely paralleling the observed increase noted above. We next compare distributional predictions of this equilibrium of our model to empirical counterparts derived from NPSAS data for 2011-12.[37]

Table 6 provides the comparison for students attending any four-year nonprofit college that NPSAS classifies as at least minimally selective, the same criteria used for our baseline 2007-08 calibration.[38] For this student population, we divided students by income into septiles of equal size, and by SAT into septiles of equal size.[39] The upper panel of Table 6 then shows the percentage of students by income and SAT. The total of all the cells sums to 100 in all cases. The lower panel in Table 6 is the model's predicted counterpart to the upper table. In computing the predicted table, we adjust for the fact that SAT is not the only ability measure that colleges use in admissions. More specifically, we assume that the logarithm of ability (*b*) used by colleges is linear in SAT and an independently distributed mean-0 and normal component (ε) that we do not observe: $ln b = \alpha_0 + \alpha_1 SAT + \varepsilon$. Recall, that we have assumed *ln b* follows the IQ distribution and has correlation with logarithm income of .4. We assume further that SAT and *ln*

[35] https://trends.collegeboard.org/sites/default/files/trends-student-aid-web-final-508-2.pdf

[36] Recall that we measure federal aid as a weighted sum of grants, work-study aid, and loans using the formula: Federal Aid = Grants + 0.33 Work-study + 0.1 Loan.

[37] Computed from NCES data using NCES PowerStats Version 1.0 on 12/20/2014. https://nces.ed.gov/datalab/

[38] We restrict the data to dependent students, as our model is intended to explain behavior of typical students. Dependent students make up the vast majority of students attending four-year institutions.

[39] Our goal in summarizing by septiles is to provide detail about the joint distribution of income and ability without undue information overload. This just reflects a judgement and is as such fairly arbitrary.

*b* have a correlation of .70. We assume the correlation of SAT and logarithm of income equals .50.[40] Thus, we assume SAT explains half the variation in ability and that the correlation between income and SAT is positive and higher than the correlation between income and ability to allow for costly development of test taking skills.

Inspection of Table 6 reveals that the predictions follow the broad pattern in the data quite well. At first glance, it appears that there is substantial over-prediction in the left-most column, but this is to some degree an artifact of the division into cells. The sum of the left-most two columns of each row of the predicted table matches well the sum of the left-most two columns of the corresponding row of the data table.

As further evidence regarding fit, we present in the first column of Table 10 a regression of the empirical values from Table 7 on the predicted values. The dependent variable is comprised of the 49 observations of the empirical values in Table 6, and the independent variable is comprised of the counterpart predicted values. The regression explains 46% of the variance in the data and the slope coefficient, .27, is significant ($p<.01$). If we combine the two left-most columns of each row and regress the resulting 42 empirical observations against the predicted counterparts, we obtain an $R^2$=.83 and slope coefficient of .59. Note that a slope coefficient of 1 would arise if the match were perfect. We would expect an estimate slope coefficient less than one due to measurement error—the estimated coefficient would be less than one if the predicted values equal the actual values plus measurement error. Overall, the distributional predictions in Table 6 and the associated regression results provide encouraging support for our model.

We next turn to separate comparison of actual and predicted values for public and private colleges. Table 7 provides the comparison for state colleges. In this and subsequent tables, we maintain the septile ranges defined for Table 6 (thus in each panel all entries continue to sum to 100). In Table 7, we see that the predicted values capture well the broad pattern in the data, with some over-prediction in the lower left of the table. The regression for these data shown in column 2 of Table 10 has an $R^2$=.38 and slope coefficient of .18. Also, as with Table 6, the sum of the left-most two columns of each row of the predicted values matches well the corresponding

[40] With given distribution of *ln b*, the assumption on the explanatory power of SAT pins down all values in the linear equation.

sum for the empirical values. Combining the left-most two columns as above, we obtain an $R^2$=.72 and a slope coefficient =.44.

Tables 8 and 9 provide comparisons of predicted private school attendance to two alternative measures of private school attendance. In Table 8 the predictions are compared to the attendance data for all students attending private schools. Here, while the broad pattern of predictions conforms to that in the data, the model under-predicts the enrollments of lower-income and lower-ability students and over-predicts enrollments of high-income and high-ability students. The regression of actual to predicted yields an $R^2$=.39 and slope coefficient of .22. Colleges may admit some low-income and low-scoring students to meet diversity objectives for under-represented student groups, objectives not incorporated in our model. Hence, in Table 9, we compare predictions of our model to attendance in selective private colleges for groups that are not under-represented—white and Asian students. As expected, the predictions of our model correspond more closely to the empirical values in Table 9. The regression for these has a slope coefficient of .70 and $R^2$=.42.

The broad congruence of the predicted values for 2011-02 to the empirical values is quite encouraging, especially in light of the very large financial aid increase that is embodied in these predictions. These comparisons provide support for use of the model to conduct the counter-factual policy analysis undertaken in Section 4.

3.4 Robustness Analysis. Many variations in the model could be analyzed. Here we consider three. The first assumes variation among private colleges in the efficiency of using resources to increase quality and thus student achievement. Specifically, we assume the lower endowed private colleges are more efficient, with higher exponents on expenditure in the quality function than the highest endowed college. College equilibrium values are reported in Panel B of Table 4 (and the footnote provides the specific parameter changes). Relative to the baseline equilibrium, Colleges 3 and 4 grow, charge higher tuition, spend more on educational resources, and increase in quality. The highest endowed college remains the highest quality with this parameterization, but it is less competitive and its quality declines.

The second variation we consider removes the price cap at the highest endowed private college, with results reported in Panel C of Table 4. Rich households with low ability students might then try to buy their way into the most elite college. Average tuition and expenditure on resources rise markedly relative to the baseline, as does average income of students.[41] Of course, the quality index rises, the college being freed from a constraint. Interestingly, while the college does allow in some rich and low ability students who pay exorbitant tuition, the college limits this substantially and the average ability of students *increases*. By increasing quality through higher expenditure on resources, the college attracts a bigger proportion of the highest ability students.

The last variation bequeaths an additional quality bump to the highest endowed private college, as though attendance there enhances prestige of graduates. Results are as intuition suggests and reported in Panel D of Table 4.

While all three variations in the model impact specific properties of equilibrium, the basic elements of equilibrium like the character of student sorting persist.

## 4 Policy Analysis

The first policy change we examine is a change in the maximum level of federal aid, this motivated by the substantially increased aid implemented under the Obama administration. We consider an increase in the maximum federal aid from $6,000 to $8,000.[42] Aggregate effects of this policy change are summarized in Table 3.[43] Overall college enrollment increases by 6 percent of the initial college population, with two thirds of this increase being in state colleges.[44] Table 11 provides a more detailed analysis of the impact of this policy on enrollment by income and ability. The upper panel of Table 11 reports percentage changes in enrollments *of the potential student population* aggregated over all colleges by income and ability decile resulting from the policy change. As shown by the shaded areas, the primary effects are substantially increased attendance by poorer and middle- and high-ability students. The ability threshold for

[41] It is not clear how to compute federal aid so we allow all students to obtain the maximum.

[42] We have as well examined an increase in the maximum aid to $9,000, as we discussed in Section 3.3. We report the detail on the $2,000 increase here because it is comparable to the state policy change we also examine below.

[43] More detailed effects of the policy experiments are provided in tables in the on-line appendix.

[44] Dynarski and Scott-Clayton (2013) summarize the causal empirical evidence on enrollment effects of increased aid: "Taken together, the quasi-experimental evidence suggests that an additional $1,000 of grant aid may increase college enrollment by 4 percentage points." In our model, the increase in maximum federal aid to $8,000 implies an average increase in federal aid among students that get positive aid of about $1,650. Thus, the predictions of our model are in line with the empirical evidence.

admission of out-of-state students to state schools rises a bit, leading to a nontrivial decreases in attendance of the lowest ability students at state colleges.[45]

Private college growth is small, but their qualities improve a bit as they spend more per student (e.g., $661 in the middle quality private college) and slightly improve their peer groups. The latter comes from a moderate substitution of some very high ability and poorer students for some not-as-high ability and rich students.[46] *Overall, the policy change does increase access of poorer students to college and to higher-quality colleges.*

The effects on student costs are of much interest. Refer to Table 3.[47] In state colleges, average federal aid rises by $880, the percent receiving aid rises from 25.7 to 34.7, mainly from more poor students that qualify entering college, and average cost of state college students declines by $900. Poor students that qualify for the maximum aid save the full $2,000 increase in federal aid. Abstracting from compositional effects, the average saving in costs among students that attend the same state college before and after the policy change is $203. The reason that this cost saving is below the amount by which average student cost declines in state colleges is because poorer students who receive a lot of aid are drawn into state colleges.

Things are very different in the private colleges because they significantly change their policies with the aid increase. Average federal aid awarded in private colleges also increases by $880 and the percentage receiving aid rises from 29.6 to 34.7. But average student cost *increases* by $370 and, restricting attention to students that would attend the same private college before and after the policy change, their average cost increases by $35. Private colleges increase expenditure and average tuition, increasing their qualities. While the cost effects are very uneven, with some poorer students saving costs as high as $2,000, rich students pay more for the quality increase with a net average cost effect close to 0. Thus, among private school students that do not change college, crowd out is approximately 100 percent.[48]

[45] The federal income tax used to finance the increased federal aid rises as does the state tax to finance increased enrollment in state colleges. The tax increases, a failure to qualify for increased aid, and the small decline in the state college quality index lead some upper-income students to exit state colleges who were near the margin of attendance (explaining most of the negative entries in the upper panel of Table 11).

[46] These results and some other results discussed below are not shown in tables here due to space constraints.

[47] Effects of the policy changes on student costs in private and public colleges across the distribution of student types are provided in the on-line appendix.

[48] Given compositional changes, measuring crowd out is not straightforward. Average federal aid in private colleges rises by $880, while average institutional aid declines by $350. Crowd out of institutional aid in private colleges of increased federal aid then equals 40 percent by this measure.

A decrease in the maximum federal aid to $4,000 has roughly symmetric effects. College attendance drops by 5.25 percent of the initial college population, with 61 percent of this in state colleges. Comparing the middle panel of Table 11 to the two lower panels of Table 5, one can determine that exit of poorer students is very substantial. Student costs in state schools that remain in the state college rise by an average of $165. Of course, poorer students that received maximum aid and remain in a state college lose the full $2,000. Private college students that remain in the same college on average face lower costs, as private colleges decrease expenditure and provide more financial aid. As in the case of a federal aid increase, the cost effects are very uneven, with students that receive full aid facing a cost increases as much as $1,300.

Recently, states have cut funding to their colleges with offsetting tuition increases. This motivates the second policy experiment we conduct. We consider a $2,000 decrease in per student state funding, accompanied by a $2,000 increase in tuition to both in- and out-of-state students. Enrollment in colleges drops substantially by 9.25 percent of the initial college population, with small growth in private college enrollments as demand shifts toward them. As one can see in the bottom panel of Table 11, most of the decreased enrollment is of poor students, but there is also non-trivial exit of middle-income students and rich low-ability students.[49] Again, the effects on the poorer students are massive. Since tuition rises by $2,000 to all state college students one might expect that federal aid would rise to compensate for the increased student cost. While this is true for students that qualify for aid $2,000 below the maximum and remain in a state college, the exit of lower income students who would receive a lot of aid and the cap on federal aid implies average federal aid in state colleges only rises by $90. Most state college students bear a cost increase of the full $2,000, and the average cost increase of those in the same state college before and after the policy change increases by $1,711. Keep in mind that the percentage receiving any federal aid is below 30 percent.[50]

Though the effects are not large, the policy change benefits private colleges as demand of students near the margin of attending a private versus state college increases. More higher-ability and not-so-high income students attend, displacing some lower-ability rich students.

[49] The latter is because private colleges no longer admit any very low ability students due to increased demand of some higher ability students that exit state colleges.

[50] The percentage receiving some federal aid in state colleges declines, but this is because of the exit of poor students. Indeed, poor students that stay do get more federal aid.

Costs to most private school students rise mainly because they increase tuition and expenditure

*Overall, effects of either reduced federal or state funding are severe for students at the low-income boundary of college attendance; both effects are mitigated to some degree by private colleges through changes in provision of institutional aid and increased admissions of some high-ability poorer students.*

## 5 Conclusions

This paper provides a general equilibrium model of the market for higher education that includes competing state and private colleges with alternative objectives, students that differ by income, ability, and unobserved idiosyncratic preference for colleges, college qualities that depend on expenditures and student abilities, and federal aid modeled to approximate U.S. policy. The model provides an appealing set of theoretical predictions, including price discrimination by private colleges manifest in the provision of need- and merit-based aid, and minimum ability admission standards at state colleges that vary across in- and out-of-state students. The quantitative version of the model does an excellent job of matching tuition and enrollment elasticity estimates and aggregate characteristics of U.S. higher education, and a credible job of predicting federal financial aid and patterns of attendance by the diverse student population.

Utilizing the model for policy analysis, we find moderate overall enrollment effects of increased federal aid, but with large effects on lower-income households. Attendance changes are concentrated in state colleges. Increased federal aid leads private colleges to substitute some lower-income and higher-ability students for somewhat less able students with higher income. Predicted effects of decreased federal aid are roughly symmetric. Decreased subsidies at state colleges coupled with higher tuition, as has characterized many states of late, has dire effects on attendance by poorer students and on student costs.

We have stressed the value of developing an equilibrium model of provision of higher education to understand aspects of equilibrium like student sorting and to perform policy analysis. The computational counterpart requires us to select parameter values, and evidence about some parameters is sparse. In addition, we have, of course, made assumptions such as specification of college objectives. We think the model is successful in characterizing basic elements of higher education, and that the model can serve as a building block for future research. Further research is needed, however, to investigate robustness of the policy implications to inclusion of features not presently in the model. In particular, it is desirable to extend the framework to consider heterogeneity across states in constraints on state colleges, to introduce for-profit colleges, and to investigate further alternative approaches to provision of federal aid. Expanding the dimensions of student heterogeneity, including to race and foreign origin, is also of interest. A more difficult extension would make endogenous the state subsidy and constraint policies. Merging the analysis with research on student application frictions is an important topic. Extending the model by introducing the market for college instructors would provide further insights. These extensions of the model can provide needed evidence on robustness of policy implications presented here while also broadening the scope of policy issues that can be investigated.

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**Appendix.** Proof of Proposition 1. Given Assumptions 5 and 6, the quality maximization problem is a strictly quasi-concave programming problem with unique solution under the condition described next. Substitute (7) into (5) and (6). Then (5) and (6) define an implicit mapping from $p_{sj}(b,y)$ into $(\theta_j, I_j)$ say $(\tilde{\theta}_j(p_{sj}(b,y)), \tilde{I}(p_{sj}(b,y)))$. If the latter is a convex set, the problem is strictly quasi-concave, which we then assume. To derive (8), write out the Lagrange function for the problem presented in (4) - (7). Suppressing the j subscript and the functional arguments, the Lagrange function is:

$$\begin{aligned} L = q + \lambda\left[\left(\iint \sum_{s=1}^{S} \pi_s p_s r_s f_s dbdy\right) + E - F - V - kI\right] \\ + \eta\left[k\theta - \iint b \sum_{s=1}^{S} \pi_s r_s f_s dbdy\right] + \Omega\left[k - \iint \sum_{s=1}^{S} \pi_s r_s f_s dbdy\right]. \end{aligned} \tag{27}$$

Compute the derivatives with respect to $\theta$, $I$, and $k$, and the first variation with respect to $p_s(b,y)$.

$$\begin{aligned} L_\theta = q_\theta + \lambda \iint \sum_{s=1}^{S} \pi_s p_s \frac{\partial r_s}{\partial q} q_\theta f_s dbdy + \eta\left[k - \iint b \sum_{s=1}^{S} \pi_s \frac{\partial r_s}{\partial q} q_\theta f_s dbdy\right] \\ - \Omega \iint \sum_{s=1}^{S} \pi_s \frac{\partial r_s}{\partial q} q_\theta f_s dbdy = 0. \end{aligned} \tag{28}$$

$$L_I = q_I + \lambda\left[\iint \sum_{s=1}^{S} \pi_s p_s \frac{\partial r_s}{\partial q} q_I f_s dbdy - k\right] - \eta \iint b \sum_{s=1}^{S} \pi_s \frac{\partial r_s}{\partial q} q_I f_s dbdy$$
$$-\Omega \iint \sum_{s=1}^{S} \pi_s \frac{\partial r_s}{\partial q} q_I f_s dbdy = 0. \quad (29)$$

$$L_k = -\lambda[V' + I] + \eta\theta + \Omega = 0. \quad (30)$$

$$L_{p_s(b,y)} = \lambda \pi_s f_s (r_s + p_s \partial r_s / \partial p_s) - \eta b \pi_s f_s \partial r_s / \partial p_s - \Omega \pi_s f_s \partial r_s / \partial p_s = 0$$
$$\forall\, p_s(b, y) \text{ with } r_s(b, y) > 0. \quad (31)$$

From (28) and (29), one obtains:

$$\frac{q_\theta}{q_I} = -\frac{\eta}{\lambda}. \quad (32)$$

Divide (30) and (31) by *λ,* yielding respectively:

$$-[V' + I] + \frac{\eta}{\lambda}\theta + \frac{\Omega}{\lambda} = 0. \quad (33)$$

$$\pi_s f_s \left[ r_s + p_s \partial r_s / \partial p_s - \frac{\eta}{\lambda} b \partial r_s / \partial p_s - \frac{\Omega}{\lambda} \partial r_s / \partial p_s \right] = 0 \ \forall\, p_s(b, y) \text{ with } r_s(b, y) > 0. \quad (34)$$

Substituting (32) and (33) into (34), after dividing through by $\partial r_s / \partial p_s$, completes the derivation.

If there is a capacity constraint, then the Lagrangian is augmented with the term $\xi[\, k - k^c \,]$, where $\xi$ is a multiplier. Proceeding as above, one obtains:

$p_s + \frac{r_s}{\partial r_s / \partial p_s} - EMC = -\xi / \lambda \ \ \forall\, p_s \text{ with } r_s > 0.$ Using that $\xi / \lambda > 0$ by the usual Envelope Theorem argument, it is implied all types with positive admissions have the same positive difference between MR and EMC, and the results reported in footnote 14 follow.

<u>Proof of Proposition 2</u>. From the first-order conditions, one can write the first variation with respect to admission of in-state and out-of-state students as:

$$L_{\gamma_s} = \lambda \pi_s r_s f_s(b, y)[a(\cdot)/\lambda + T_s + z - EMC_s(b)] \quad (35)$$

$$L_{\gamma_{so}} = \lambda\left(\sum_{t \neq s} \pi_t r_{ts} f_t(b, y)\right)[T_{so} + z - EMC_s(b)] \quad (36)$$

where $\lambda > 0$ is the Lagrange multiplier associated with the budget constraint (13). From (35) and (36), using the feasibility constraints, one obtains the results.

Table 1: Parameter Values

| | |
|---|---|
| *State College Tuition and Subsidy*[*] | |
| In-state Students | 6.2 |
| Out-of-state Students | 15.1 |
| Per-student Subsidy | 8.5 |
| *Private College Endowments and Price Caps*[*] | |
| Endowments | 0.199, 0.543, 3.470 |
| Price Caps | 22.5, 24.5, 32.5 |
| *Ability & Income Distribution* | |
| Ability | $ln(b) \sim N(1.0, 0.15)$ |
| Income | $ln(y + 41,536) \sim N(11.46, 0.402)$ |
| Ability-Income Correlation | 0.40 |
| *Utility Function* | |
| $\alpha$ | 20 |
| $\gamma$ | 0.15 |
| $\omega$ | 0.155 |
| $\beta$ | 0.8 |
| $a_0$ | 2.02665 |
| $\delta_R$[**] | 1.0525 |
| Non-tuition Costs[*] | 10.25 |
| *Cost Function*[*] | |
| $F$ | 0.24 |
| $v1$ | 0 |
| $v2$ | 25 |
| *Federal Aid*[*] | |
| Maximum Aid | 6 |

[*]Measured in thousand dollars.

[**]We set $\delta_j = 1$ at state colleges.

Table 2: Parameter Estimates: Income Distribution

| | Coefficient | Std. Error |
|---|---|---|
| mean | 11.46 | 0.126 |
| std deviation | -0.402 | 0.044 |
| location parameter | 41,536 | 11,867 |

Table 3: Aggregates: Baseline and Policy Changes*

| | Data | Baseline | MaxFed=8 | MaxFed=4 | StChg=2** |
|---|---|---|---|---|---|
| Total enrollment | 40% | 40.0% | 42.5% | 37.9% | 36.3% |
| Share of state schools | 70% | 70.0% | 69.8% | 70.5% | 62.9% |
| Proportion of in-state at state | 90% | 92.7% | 92.2% | 93.0% | 92.7% |
| Average fed. aid (state schools) | 1.25-1.5 | 1.20*** | 2.08 | 0.60 | 1.29 |
| Average fed. aid (private schools) | 2-2.5 | 1.59*** | 2.47 | 0.89 | 1.43 |
| Average institutional aid | 1.95 | 1.83 | 1.48 | 2.32 | 0.94 |
| Private tuition average | 23.40 | 23.70 | 23.99 | 23.29 | 24.48 |
| State tuition average | 7.09 | 6.85 | 6.89 | 6.82 | 8.85 |
| Fraction receiving fed. aid (state) | 30-40% | 25.7% | 33.0% | 19.0% | 27.3% |
| Fraction receiving fed. aid (private) | 30-40% | 29.6% | 34.7% | 24.4% | 26.9% |
| Average student cost† (state) | | 15.96 | 15.06 | 16.48 | 17.80 |
| Average student cost† (private) | | 31.40 | 31.77 | 32.65 | 33.30 |
| Change in student's cost, conditional‡ (state) | | | -0.203 | 0.165 | 1.711 |
| Change in student's cost, conditional‡ (private) | | | 0.035 | -0.238 | 0.853 |
| Increase in private tuition per $10,000 of income | 0-0.44 | 0.28 | | | |
| Decrease in private tuition per 1 st.dev. of ability | 0-2.39 | 0.77 | | | |
| Enrollment elasticity of institutional aid | 0.70 | 0.62-0.75 | | | |

* Dollar amounts are measured in thousands.
** State tuition increases and state subsidy decreases by the same amount.
*** The averages conditional on getting any aid are 4.67 at state colleges and 5.37 at private colleges.
† These amounts include the non-tuition costs.
‡ This is the change in average costs of students attending the same college before and after the policy change.

Table 4: College Values*

Panel A: Baseline Values

| $j$ | $k_j$ | $\theta_j$ | $I_j$ | $q_j$ | Ave.Tuit. | Ave.Fed.Aid | Ave.Inc | Prop. Price Cap |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.1401 | 3.006 | 10.13 | 1.182 | 6.85 | 1.20 | 83.25 | - |
| 2 | 0.1401 | 3.006 | 10.13 | 1.182 | 6.85 | 1.20 | 83.25 | - |
| 3 | 0.0481 | 3.125 | 14.91 | 1.328 | 20.91 | 1.77 | 111.88 | 39% |
| 4 | 0.0442 | 3.140 | 16.77 | 1.354 | 22.75 | 1.62 | 117.71 | 39% |
| 5 | 0.0275 | 3.211 | 24.18 | 1.438 | 30.12 | 1.23 | 139.57 | 39% |

Panel B: Variation in Efficiency among Private Colleges**

| $j$ | $k_j$ | $\theta_j$ | $I_j$ | $q_j$ | Ave.Tuit. | Ave.Fed.Aid | Ave.Inc | Prop. Price Cap |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.1376 | 3.009 | 10.15 | 1.182 | 6.84 | 1.23 | 82.13 | - |
| 2 | 0.1376 | 3.009 | 10.15 | 1.182 | 6.84 | 1.23 | 82.13 | - |
| 3 | 0.0523 | 3.098 | 16.04 | 1.355 | 21.74 | 1.36 | 118.77 | 60% |
| 4 | 0.0453 | 3.131 | 17.16 | 1.365 | 23.05 | 1.57 | 118.64 | 44% |
| 5 | 0.0273 | 3.222 | 23.23 | 1.429 | 29.24 | 1.56 | 132.03 | 27% |

Panel C: No Price Cap at College 5

| $j$ | $k_j$ | $\theta_j$ | $I_j$ | $q_j$ | Ave.Tuit. | Ave.Fed.Aid | Ave.Inc | Prop. Price Cap |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.1426 | 3.006 | 10.09 | 1.181 | 6.84 | 1.18 | 83.19 | - |
| 2 | 0.1426 | 3.006 | 10.09 | 1.181 | 6.84 | 1.18 | 83.19 | - |
| 3 | 0.0486 | 3.118 | 14.96 | 1.329 | 20.91 | 1.76 | 111.95 | 39% |
| 4 | 0.0448 | 3.133 | 16.80 | 1.354 | 22.74 | 1.64 | 117.60 | 39% |
| 5 | 0.0214 | 3.296 | 33.66 | 1.519 | 41.93 | 6.00 | 154.37 | - |

Panel D: Exogenous Quality Advantage at College 5***

| $j$ | $k_j$ | $\theta_j$ | $I_j$ | $q_j$ | Ave.Tuit. | Ave.Fed.Aid | Ave.Inc | Prop. Price Cap |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.1394 | 3.005 | 10.14 | 1.182 | 6.84 | 1.20 | 83.05 | - |
| 2 | 0.1394 | 3.005 | 10.14 | 1.182 | 6.84 | 1.20 | 83.05 | - |
| 3 | 0.0477 | 3.125 | 14.62 | 1.324 | 20.64 | 1.90 | 108.72 | 32% |
| 4 | 0.044 | 3.139 | 16.45 | 1.350 | 22.46 | 1.76 | 114.27 | 33% |
| 5 | 0.0295 | 3.219 | 25.88 | 1.471 | 31.28 | 0.86 | 147.86 | 62% |

*Dollar amounts are measured in thousands. However, in calculating the quality index, $I_j$ is measured in tens of thousands, a normalization.

**Colleges differ in efficiency in their use of instructional expenditures. Specifically, we set $\omega$ for colleges 3, 4, and 5 as 0.175, 0.165, and 0.155, respectively.

***The quality premium at College 5 is set as 1.065 rather than 1.0525, the latter being the quality premium at Colleges 3 and 4.

Table 5: College Attendance Proportions

**Top Private College**

*Ability Deciles*

| *Income Deciles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
|---|---|---|---|---|---|---|---|---|---|---|
| *10* | 0% | 9% | 12% | 13% | 14% | 15% | 15% | 17% | 19% | 24% |
| *9* | 0% | 1% | 1% | 1% | 2% | 2% | 3% | 4% | 5% | 10% |
| *8* | 0% | 0% | 0% | 1% | 1% | 2% | 3% | 5% | 8% | 16% |
| *7* | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 1% | 2% | 6% |
| *6* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 2% |
| *5* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *4* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *3* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *2* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *1* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

**All Private Colleges**

| *Income Deciles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
|---|---|---|---|---|---|---|---|---|---|---|
| *10* | 20% | 37% | 45% | 50% | 53% | 54% | 55% | 57% | 59% | 67% |
| *9* | 2% | 7% | 11% | 13% | 16% | 18% | 21% | 24% | 30% | 42% |
| *8* | 0% | 1% | 2% | 3% | 5% | 8% | 12% | 16% | 22% | 38% |
| *7* | 0% | 1% | 2% | 4% | 7% | 11% | 17% | 25% | 35% | 54% |
| *6* | 0% | 0% | 0% | 1% | 1% | 3% | 5% | 10% | 19% | 41% |
| *5* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 3% | 10% |
| *4* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *3* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *2* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *1* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

**State Colleges**

| *Income Deciles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
|---|---|---|---|---|---|---|---|---|---|---|
| *10* | 20% | 34% | 40% | 43% | 43% | 44% | 44% | 43% | 40% | 33% |
| *9* | 10% | 28% | 45% | 57% | 66% | 71% | 73% | 73% | 69% | 58% |
| *8* | 4% | 14% | 26% | 41% | 54% | 65% | 73% | 76% | 74% | 62% |
| *7* | 2% | 5% | 11% | 20% | 30% | 41% | 50% | 57% | 57% | 44% |
| *6* | 0% | 2% | 4% | 8% | 13% | 22% | 32% | 46% | 57% | 53% |
| *5* | 1% | 2% | 5% | 10% | 16% | 26% | 39% | 55% | 73% | 83% |
| *4* | 1% | 3% | 6% | 11% | 18% | 28% | 41% | 58% | 76% | 92% |
| *3* | 0% | 0% | 1% | 1% | 3% | 5% | 8% | 14% | 27% | 56% |
| *2* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 3% |
| *1* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

Table 6: Attendance Percentages in All Colleges by SAT and Income Septiles

**Empirical Attendance Percentages in All Colleges**

*SAT Septiles*

| *Income Septiles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|
| *7* | 1.02 | 1.40 | 1.65 | 2.11 | 2.12 | 2.70 | 3.21 |
| *6* | 1.27 | 1.90 | 1.78 | 1.95 | 2.12 | 2.51 | 2.77 |
| *5* | 1.48 | 1.69 | 2.38 | 2.12 | 2.08 | 2.31 | 2.32 |
| *4* | 1.88 | 2.22 | 2.16 | 2.08 | 2.00 | 1.89 | 1.97 |
| *3* | 2.08 | 2.23 | 2.19 | 1.95 | 2.09 | 2.11 | 1.65 |
| *2* | 3.10 | 2.69 | 2.08 | 1.89 | 1.71 | 1.66 | 1.27 |
| *1* | 3.87 | 2.61 | 1.84 | 1.94 | 1.52 | 1.36 | 1.06 |

**Predicted Attendance Percentages in All Colleges**

| *Income Septiles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|
| *7* | 2.52 | 0.41 | 1.31 | 1.74 | 2.26 | 1.95 | 4.08 |
| *6* | 2.84 | 0.42 | 1.39 | 2.06 | 2.49 | 1.40 | 3.68 |
| *5* | 2.76 | 0.39 | 1.62 | 2.67 | 2.54 | 0.94 | 3.37 |
| *4* | 1.86 | 1.04 | 3.22 | 2.80 | 1.55 | 1.33 | 2.49 |
| *3* | 2.99 | 2.05 | 2.30 | 2.12 | 1.84 | 2.05 | 0.92 |
| *2* | 5.89 | 1.61 | 1.78 | 2.07 | 2.11 | 0.78 | 0.05 |
| *1* | 7.28 | 1.25 | 2.75 | 2.13 | 0.81 | 0.06 | 0.00 |

(The SAT and income septiles are from the NPSAS data conditional on the student being a dependent and attending any non-profit four-year colleges that is at least minimally selective. The SAT septiles are 400, 860, 950, 1025, 1090, 1170, and 1260; and the income septiles are $0, $23,750, $43,750, $66,900, $88,500, $112,751, and $154,000.)

Table 7: Attendance Percentages in State Colleges by SAT and Income Septiles

**Empirical Attendance Percentages in State Colleges**

*SAT Septiles*

| *Income Septiles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|
| *7* | 1.03 | 1.54 | 1.66 | 2.18 | 2.11 | 2.40 | 2.28 |
| *6* | 1.31 | 2.18 | 1.94 | 2.13 | 2.24 | 2.43 | 2.06 |
| *5* | 1.69 | 1.88 | 2.27 | 2.21 | 2.08 | 2.27 | 2.05 |
| *4* | 1.94 | 2.44 | 2.36 | 2.11 | 2.18 | 1.80 | 1.38 |
| *3* | 2.17 | 2.34 | 2.38 | 2.05 | 2.18 | 2.04 | 1.40 |
| *2* | 3.19 | 2.72 | 2.16 | 2.08 | 1.84 | 1.60 | 0.99 |
| *1* | 4.10 | 2.84 | 2.12 | 1.87 | 1.54 | 1.34 | 0.87 |

**Predicted Attendance Percentages in State Colleges**

| *Income Septiles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|
| *7* | 1.58 | 0.20 | 0.54 | 0.75 | 1.09 | 0.73 | 1.72 |
| *6* | 2.95 | 0.36 | 1.20 | 1.75 | 1.89 | 0.88 | 3.05 |
| *5* | 3.93 | 0.51 | 1.88 | 2.96 | 2.42 | 0.65 | 3.76 |
| *4* | 4.19 | 1.56 | 3.34 | 2.34 | 0.99 | 1.50 | 2.48 |
| *3* | 3.68 | 1.84 | 1.19 | 1.11 | 1.38 | 1.42 | 0.30 |
| *2* | 7.44 | 1.84 | 2.18 | 2.58 | 2.54 | 0.78 | 0.04 |
| *1* | 10.45 | 1.79 | 3.95 | 3.06 | 1.16 | 0.08 | 0.00 |

(The SAT and income septiles are from the NPSAS data conditional on the student being a dependent and attending any non-profit four-year colleges that is at least minimally selective. The SAT septiles are 400, 860, 950, 1025, 1090, 1170, and 1260; and the income septiles are $0, $23,750, $43,750, $66,900, $88,500, $112,751, and $154,000.)

Table 8: Attendance Percentages in Private Colleges by SAT and Income Septiles

**Empirical Attendance Percentages in Private Colleges**

| Income Septiles \ *SAT Septiles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|
| *7* | 0.99 | 1.10 | 1.62 | 1.96 | 2.16 | 3.33 | 5.20 |
| *6* | 1.18 | 1.28 | 1.42 | 1.58 | 1.85 | 2.70 | 4.31 |
| *5* | 1.04 | 1.29 | 2.63 | 1.92 | 2.08 | 2.42 | 2.89 |
| *4* | 1.77 | 1.74 | 1.72 | 2.01 | 1.61 | 2.08 | 3.23 |
| *3* | 1.88 | 2.00 | 1.78 | 1.73 | 1.90 | 2.27 | 2.19 |
| *2* | 2.92 | 2.63 | 1.92 | 1.50 | 1.43 | 1.79 | 1.86 |
| *1* | 3.36 | 2.12 | 1.22 | 2.07 | 1.46 | 1.39 | 1.48 |

**Predicted Attendance Percentages in Private Colleges**

| Income Septiles | *1* | *2* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|
| *7* | 0.02 | 0.86 | 3.63 | 4.84 | 5.11 | 5.24 | 12.23 |
| *6* | 0.02 | 0.55 | 2.33 | 3.31 | 4.33 | 3.27 | 5.56 |
| *5* | 0.01 | 0.21 | 1.06 | 1.99 | 2.78 | 1.57 | 2.46 |
| *4* | 0.01 | 0.53 | 2.16 | 2.35 | 1.61 | 0.96 | 1.82 |
| *3* | 0.26 | 1.69 | 5.40 | 5.39 | 3.47 | 2.99 | 2.84 |
| *2* | 0.68 | 1.18 | 1.22 | 1.31 | 1.37 | 1.13 | 0.28 |
| *1* | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

(The SAT and income septiles are from the NPSAS data conditional on the student being a dependent and attending any non-profit four-year colleges that is at least minimally selective. The SAT septiles are 400, 860, 950, 1025, 1090, 1170, and 1260; and the income septiles are $0, $23,750, $43,750, $66,900, $88,500, $112,751, and $154,000.)

Table 9: Attendance Percentages in Highly Selective Private Colleges of Whites and Asians

**Empirical Attendance Percentages in Highly Selective Priv. Colleges of Whites and Asians**

| Income Septiles \ *SAT Septiles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|
| *7* | 0.57 | 0.66 | 2.25 | 1.91 | 2.74 | 6.06 | 9.75 |
| *6* | 0.73 | 0.69 | 0.91 | 1.72 | 1.2 | 3.26 | 8.98 |
| *5* | 0.38 | 0.47 | 2.28 | 0.95 | 1.55 | 2.36 | 6.54 |
| *4* | 0.73 | 0.35 | 0.79 | 1.62 | 1.5 | 2.93 | 5.67 |
| *3* | 0.61 | 0.83 | 1.27 | 0.67 | 1.84 | 2.25 | 3.88 |
| *2* | 0.51 | 1.32 | 1.25 | 0.99 | 0.99 | 2.71 | 4.24 |
| *1* | 0.92 | 0.56 | 0.59 | 1.3 | 0.58 | 0.87 | 2.27 |

**Predicted Attendance Percentages in Private Colleges**

| Income Septiles | *1* | *2* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|
| *7* | 0.02 | 0.86 | 3.63 | 4.84 | 5.11 | 5.24 | 12.23 |
| *6* | 0.02 | 0.55 | 2.33 | 3.31 | 4.33 | 3.27 | 5.56 |
| *5* | 0.01 | 0.21 | 1.06 | 1.99 | 2.78 | 1.57 | 2.46 |
| *4* | 0.01 | 0.53 | 2.16 | 2.35 | 1.61 | 0.96 | 1.82 |
| *3* | 0.26 | 1.69 | 5.40 | 5.39 | 3.47 | 2.99 | 2.84 |
| *2* | 0.68 | 1.18 | 1.22 | 1.31 | 1.37 | 1.13 | 0.28 |
| *1* | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

(The SAT and income septiles are from the NPSAS data conditional on the student being a dependent and attending any non-profit four-year colleges that is at least minimally selective. The SAT septiles are 400, 860, 950, 1025, 1090, 1170, and 1260; and the income septiles are $0, $23,750, $43,750, $66,900, $88,500, $112,751, and $154,000.)

Table 10: Model Fit to Attendance Data: Regression Results†

| **Model:** | **All Colleges** | **State Colleges** | **All Private** | **Private Very Selective White/Asian** |
|---|---|---|---|---|
| Constant | 1.491*** | 1.671*** | 1.600*** | 0.826*** |
| | (0.090) | (0.098) | (0.127) | (0.233) |
| Slope | 0.269*** | 0.181*** | 0.216*** | 0.595*** |
| | (0.039) | (0.036) | (0.056) | (0.126) |
| $R^2$ | 0.46 | 0.38 | 0.37 | 0.42 |

†The dependent variable in each model equals the empirical bivariate septile percentage regressed on a constant and the predicted bivariate septile percentage for the corresponding school set. In the case of the private college regressions, the model predicted value is for all private colleges. Robust standard errors are in parenthesis.
***Indicates significance at the 1% level.

Table 11: Change in Total Enrollment Proportions for All Colleges Combined

**Maximum Federal Aid = $8,000**

*Ability Deciles*

| *Income Deciles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
|---|---|---|---|---|---|---|---|---|---|---|
| *10* | -13% | -2% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *9* | -2% | -2% | -1% | -1% | -1% | -1% | 0% | 0% | 0% | 0% |
| *8* | -1% | -1% | -1% | -2% | -2% | -2% | -1% | -1% | 0% | 0% |
| *7* | 0% | 0% | 0% | 0% | -1% | 0% | 0% | 0% | 1% | 0% |
| *6* | 0% | 0% | 0% | 0% | 1% | 2% | 3% | 4% | 3% | 1% |
| *5* | 0% | 0% | 0% | 0% | -1% | -1% | -1% | 0% | 0% | 0% |
| *4* | 1% | 3% | 7% | 11% | 17% | 20% | 22% | 19% | 13% | 5% |
| *3* | 0% | 1% | 3% | 6% | 10% | 17% | 24% | 32% | 38% | 31% |
| *2* | 0% | 0% | 0% | 0% | 0% | 1% | 2% | 4% | 7% | 20% |
| *1* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

**Maximum Federal Aid = $4,000**

| *Income Deciles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
|---|---|---|---|---|---|---|---|---|---|---|
| *10* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| *9* | 0% | 0% | 1% | 1% | 1% | 1% | 0% | 0% | 0% | 0% |
| *8* | 0% | 1% | 1% | 2% | 2% | 1% | 1% | 1% | 0% | 0% |
| *7* | 0% | 0% | 0% | 0% | 0% | 0% | -1% | -1% | -1% | 0% |
| *6* | 0% | 0% | 0% | 0% | -1% | -1% | -2% | -2% | -2% | -1% |
| *5* | 0% | 0% | -1% | -1% | -2% | -3% | -3% | -3% | -3% | -1% |
| *4* | 0% | -2% | -4% | -8% | -13% | -19% | -25% | -31% | -30% | -17% |
| *3* | 0% | 0% | -1% | -1% | -2% | -4% | -7% | -12% | -21% | -34% |
| *2* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | -1% | -3% |
| *1* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

**State Change = $2,000**

| *Income Deciles* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
|---|---|---|---|---|---|---|---|---|---|---|
| *10* | -15% | -19% | -6% | 1% | 0% | 0% | 0% | 0% | 0% | 0% |
| *9* | -4% | -11% | -8% | -3% | -3% | -2% | -1% | -1% | 0% | 0% |
| *8* | -2% | -5% | -8% | -8% | -9% | -9% | -6% | -4% | -2% | 0% |
| *7* | -1% | -3% | -5% | -6% | -9% | -12% | -12% | -9% | -4% | -1% |
| *6* | 0% | -1% | -1% | -3% | -5% | -7% | -9% | -10% | -7% | -2% |
| *5* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 0% | 0% |
| *4* | 0% | -2% | -4% | -7% | -12% | -17% | -23% | -28% | -26% | -14% |
| *3* | 0% | 0% | -1% | -1% | -2% | -4% | -7% | -11% | -20% | -31% |
| *2* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | -1% | -3% |
| *1* | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

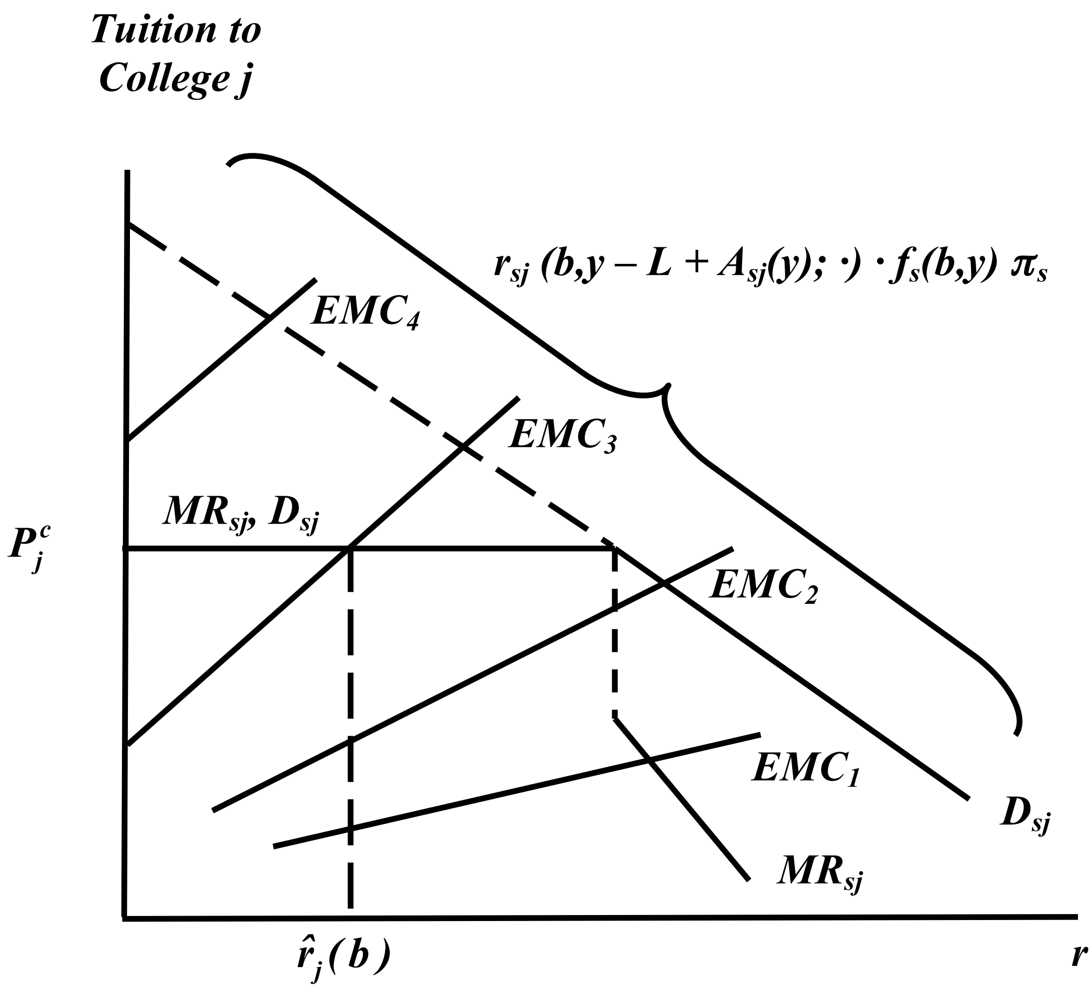
Tuition to College j
$r_{sj}\ (b,y - L + A_{sj}(y); \cdot) \cdot f_s(b,y)\ \pi_s$
$EMC_4$
$EMC_3$
$MR_{sj}, D_{sj}$
$P_j^c$
$EMC_2$
$EMC_1$
$D_{sj}$
$MR_{sj}$
$\hat{r}_j(b)$
r

**Figure 1**