

COLLEGE ASSIGNMENT AS A LARGE CONTEST

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ABSTRACT. We develop a model of college assignment as a large contest wherein students with heterogeneous abilities compete for seats at vertically differentiated colleges through the acquisition of productive human capital. We use a continuum model to approximate the outcomes of a game with large, but finite, sets of colleges and students. The continuum approximation lends tractability to a rich model for studying investment incentives in rank-order competitions. By incorporating two common families of affirmative action mechanisms into our model, admissions preferences and quotas, we can show that (legal) admissions preference schemes and (illegal) quotas have the same sets of equilibria including identical outcomes and investment strategies. Finally, we explore the welfare costs of using human capital accumulation to compete for college admissions. We define the cost of competition as the welfare difference between a color-blind admissions contest and the first-best outcome chosen by an omniscient social planner. Using a calibrated version of our model, we find that the cost of competition is equivalent to a loss of \$91,795 in NPV of lifetime earnings.

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JEL subject classification: D44, C72, I20, I28, L53.

1. INTRODUCTION

There are many economically salient features of the competition between students for admission to college. An ideal model would include heterogeneity amongst the colleges in terms of quality, allow for differences amongst the students in terms of ex-ante ability, and endogenize the decisions students make to compete for admission. For many policy questions, it is also necessary to allow for asymmetric admissions policies that grant preferential treatment to the children of alumni (so-called “legacy” status) or students from underrepresented demographic backgrounds (affirmative action). In the latter case, a further complication arises: a primary motivation for policies like affirmative action is the idea of systematic a priori asymmetries between students due to socioeconomic factors (e.g., access to relevant resources like high-quality primary and secondary school education). While many models include one or two of the above factors, providing a tractable model of the market that includes all four features—college heterogeneity,

student heterogeneity, a priori cost asymmetry, and asymmetric allocation mechanisms—has proven difficult.

A primary reason for the difficulty is the dual role played by human capital (HC) in college admissions. First, a student’s HC is a durable asset which yields a direct economic return, leading to what we call a *productive channel* of investment incentives. This channel is present in the complete-information assortative matching model of Becker [6]. Second, because each student’s ex-ante ability is private information, colleges must rely on observable measures of HC production in order to separate high-ability students from their lower-ability counterparts when deciding who will be admitted to each college. Because of this, increasing HC yields an additional, indirect benefit since students who invest more also gain access to higher quality match partners in the college admissions market. The resulting *competitive channel* of incentives resembles the signaling incentives analyzed in the seminal model of Spence [72].

We model the college admissions market as a contest wherein colleges are rank-ordered and students compete for admission by endogenously choosing the level of HC to accrue prior to a rank-order admissions contest. While this model is difficult to solve when it includes a finite number of students and colleges, we show that a more tractable limit model with a continuum of colleges and students closely approximates the finite model with many agents. More formally, we show that the equilibria of the finite game must approach the unique equilibrium of the limit model as the number of students increases.

To understand why a large market setting might simplify things, consider a student (or a student’s parents) that is deciding how much effort to exert in school with an eye toward applying to colleges. If the student wants to ascertain whether she is likely to be admitted to a school with a given GPA and SAT score, she does not need to consider the other students who might also be applying or the strategies they are employing. Instead, she simply consults a college guide that describes the qualifications of previously admitted students. Since the aggregated choices of many market players produces a high degree of predictability in these (endogenous) admissions criteria, she can have confidence if she meets the criterion at a given school that admission is likely.¹

Our goal is to provide a theoretical model that can serve as a foundation for empirical work as well a tool for market design. In addition, we use our model to prove economically important results about affirmative action and its role in the market for college admissions. Although we focus on our particular application, we believe that our framework for approximating contests with many agents using a model with a continuum of agents could prove useful. For example, one might imagine that the grant funding process used by government agencies (e.g., the National Science Foundation in the U.S.)

¹ Although this example and our main analysis are focused on college admissions, the basic insight regarding the tractability and applicability of limit games as approximations to real-world contests generalizes far outside the context of college admissions and affirmative action.

might be approximated as a contest with many prizes (grants) that vary in quality (size of the grant) that are competed for by scholars of differing innate ability. Our hope is that the fruitfulness of our analytical structure as applied to our particular application might inspire other researchers to utilize similar methods in theoretical and empirical projects in other areas.

Now we turn to our first goal, the analysis of different mechanisms that have been used to implement affirmative action schemes.² An affirmative action system implemented through a *quota* reserves separate pools of seats for different groups of students, and each student can only compete for the seats reserved for his or her group. Many different quota systems are possible, and each such system differs in the sets of college seats reserved for each group. In an *admissions preference* scheme, all applicants compete for the same pool of seats, but the fashion in which an applicant is ranked depends on the applicant's demographics.

We show that given any equilibrium of any quota (admissions preference) system, one can design an admissions preference (quota) system with an equilibrium that results in the same school assignments and HC choices. From a methodological viewpoint, the equivalence of these mechanisms allows us to focus on the easier problem of designing an optimal quota system when we compute the second-best college assignment system. The equivalence of the admissions preference and quota schemes also throws new light on the arguments about the legality of affirmative action in the United States. The U.S. Supreme Court has previously ruled that quota systems violate the 14th amendment of the U.S. Constitution, but certain forms of admissions preference systems are legal. As these two forms of affirmative action are usually compared in terms of their outcomes in the legal arguments made, our result helps explain why the U.S. legal system has had difficulty drawing a sharp line between constitutional and unconstitutional forms of affirmative action.

Our second policy goal is to study the welfare effects on students of the costly competition for college admissions. As noted in the recent "Turning the Tide" ([74]) report produced by the Harvard Graduate School of Education, college applicants exert large amounts of real effort engaging in tasks with (what appears to be) the sole aim of improving their chances of being accepted at a desirable school. Education researchers have consistently shown that students in high performing schools suffer psychological costs during middle and high school (Luthar and Becker [54], Galloway et al. [37]), which suggests that the competitive pressures cause significant welfare losses. Presumably parents, who may serve as the source of much of the pressure on these students, are also likely

²Although this paper focuses on affirmative action in the context of U.S. college admissions, the US government has mandated AA practices in various areas of the economy where it has influence, including education, employment, and procurement. AA has been widely implemented outside the United States in places such as Malaysia, Northern Ireland, India, and South Africa. For an in-depth discussion of AA implementations around the world, see Sowell [71].

to incur costs both in terms of time spent engaging with a child's school work as well as inferior relationships within the family.

We define the *cost of competition* as the difference in average payoffs between the first-best outcome generated by an omniscient social planner and the outcome generated by a color-blind college admissions contest. In the first-best outcome, the omniscient social planner assortatively assigns students to schools by their type before investment occurs. Each student then chooses the optimal HC level given her assignment, and match utilities are realized as a function of the student's HC and the quality of her match partner. In such a scenario, only Beckerian productive incentives exist, and both the college assignments and the HC investment choices are efficient. To achieve assortativity when the students' types are private information, colleges use the students' HC choices to produce a separating equilibrium wherein high-ability students can be distinguished from their lower-ability counterparts. In the equilibrium of the color-blind model, students are assigned to schools assortatively by observed HC output levels after the investment stage, giving rise to additional Spencerian competitive incentives. Students now choose a wastefully high level of HC (i.e., above the Becker optimum from a first-best assignment) in order to reveal their types to colleges and keep their lower-ability competitors at bay.

We use a calibrated version of our model drawn from Hickman [44] to characterize the welfare implications of the dual role of HC investment. We find that the cost of competition per student is equivalent to a drop of \$91,795 in the net present value of lifetime income. Since the competition by each student imposes negative externalities on higher ability students, we find that students of above average ability suffer the largest losses. Interestingly, students of the very highest ability suffer lower losses as these students are naturally inclined to accrue large human capital levels even without competitive pressures.³

Next we compute the second-best contest design. We use our limit model to formalize an optimal control problem that computes the welfare maximizing quota system subject to incentive compatibility and feasibility constraints. This problem is numerically much easier than finding the optimal admissions preference scheme, which illustrates the methodological importance of our proof of the equivalence between admissions preference and quota schemes.

In order to limit the cost of competition, the second-best contest divides the colleges into an interval of low quality schools and an interval of high quality schools with one interval assigned to each demographic group. By limiting the space of possible prizes, the planner limits the power of the competitive channel of incentives. Since the minority

³ Our welfare analysis focuses on the cost of competition imposed upon the student. It is likely that externalities from at least two sources alleviate some of the welfare loss. First, students with a high level of human capital may increase the quality of the college they attend, which is a positive externality for the other students. Second, citizens with a high level of human capital may generate an externality for society more broadly.

students have higher HC production costs, on average—due to socioeconomic factors and a priori resource allocations correlated with race—the second-best contest assigns the minority students seats at the worst colleges and nonminority students seats at the best colleges. We do not view this as a serious policy recommendation as it cuts against what is allowed by either law or a basic sense of fairness. However, on an academic level it serves to highlight the tension between welfare and fairness in this context.

Obviously this conclusion is unsettling. On the one hand, the cost of competition is (surprisingly) high, and yet on the other hand the second-best solution is unpalatable due to a concern for fairness. We hope to convince the reader that (1) the welfare costs are significant and (2) there is no obvious method for rectifying the welfare losses within the current contest structure for college admissions. In short, we believe that the welfare costs are more significant than one might have expected and that finding a solution is harder than one might have hoped.

The remainder of this paper has the following structure: in Section 2, we briefly discuss the relation between this work and the previous literature on college admissions and AA. In Section 3, we give an overview of the full model of competitive human capital investment and describe the college assignment contest we study. In Section 4 we introduce the limit model with a continuum of students and prove that equilibria of the limit model are approximate equilibria of the finite model of Section 3. In Section 5 we prove that quota and admissions preference schemes admit the same set of equilibrium outcomes and discuss the practical ramifications of this result. In Section 6 we turn to the welfare analysis of the cost of competition. Finally, in Section 7 we consider an extension to a model where the HC choices are observed by the colleges with noise. Online Appendix XXX contains a brief overview of the data sources and estimation techniques used to calibrate our model in Section 6, and Online Appendix D provides a comparative statics result for the limit model that may be of independent interest, although we do not leverage it in our current study.

2. PREVIOUS LITERATURE

Our work bridges the literatures on centralized and decentralized college admissions. One of the corner stones of the modern literature on matching without transfers is the model of centralized college admissions presented in Gale and Shapley [36]. This paper and its many follow-on works focus on how to achieve fair, incentive compatible outcomes in two-sided markets where the students and colleges can have heterogeneous preferences over agents on the other side of the market. The key advantage of this modeling approach relative to the contest structure we employ is that extremely diverse preferences can exist on both sides of the market, whereas we assume that all of the students and the colleges agree on the best agents on the other side of the market. However, the richness of the preferences admitted by most models building on Gale and Shapley

[36] makes it very difficult to include an element of endogenous student quality (i.e., endogenous human capital), which is the focus of our research.

Of the papers in this literature, the closest are Azevedo and Leshno [5] and Bodoh-Creed [10], both of which provide models that approximate a finite Gale-Shapley college admissions problem with a model with a finite set of schools and a continuum of students. These papers assume a finite set of schools due to technical difficulties related to modeling a continuum of random variables.⁴ Our contest model restricts the students' preferences sufficiently that we can accommodate a continuum of colleges. In a public-school assignment settings in the U.S., there are usually only a small number of schools - for example, Boston Public Schools has only 28 high school programs for students that do not require english learner or special education services. In our setting there are over 1200 schools with the largest enrolling less than 0.7% of all Freshman and the average school enrolling 0.1% of all Freshman.⁵ In addition to providing traction in our analysis, we believe that the assumption of a continuum of colleges is a realistic representation of our setting.

Our paper fits within the literature on centralized models of college admissions, although it differs from most of the previous literature in several substantive fashions. Our contest approach simplifies the strategic interactions within our model, which allows us to include endogenous student human capital decisions within a flexible model of college quality and innate student ability. From a policy standpoint, our focus is on the level of student effort, which we argue causes significant losses of student welfare. We also prove that our model provides an approximation of a more realistic, but analytically and computationally intractable, model with a finite number of agents. From an empirical standpoint, our goal is to provide a model with a continuum of students and colleges that can be readily taken to the data, and our analysis provides a proof of concept that our large market model is a useful tool in practice.

There is also a growing literature on decentralized college admissions that focuses on congestion problems. In a decentralized college admissions problem, colleges must tune their admissions policies to admit the best students in the presence of college capacity constraints and uncertainty regarding where accepted students will finally enroll. Papers including Avery and Levin [4]; Avery, Lee, and Roth [3]; and Che and Koh [18] study the strategic responses of colleges to this problem, how applicants respond to these programs, and the resulting welfare effects. Many of these papers analyze congestion relieving systems such as "early admissions" that induce students to apply to a single college in

⁴Specifically, if there were a continuum of colleges, then a flexible model of priorities would require that each student be assigned a continuum of priorities. Technical issues such as the measurability of expectations become very difficult unless either more exotic mathematical structures are used (e.g., Loeb spaces) or the modeler places restrictions on how a student's priority at one school is related to her priority at other schools in ways that are difficult to motivate from the actual practice of most matching mechanisms.

⁵These numbers are drawn from Hickman [44].

advance of the regular admissions process. These early admissions processes have some resemblance to the second-best college admissions process that divides the students into separate contests, although the welfare effects of congestion are orthogonal to our focus on the cost of excessive competition for admission.

Given our contest model, Halafir et al. [43] is of particular interest. Halafir et al. [43] considers the winners and losers from centralized and decentralized admissions, where the centralized system is modeled as a contest for admission to one of two vertically differentiated colleges. Although the model of centralized admissions that Halafir et al. [43] studies is more specialized than the model we present, the specificity enables the authors to compare the outcomes with a decentralized system and generate predictions that are tested experimentally.

Chade, Lewis, and Smith [15] studies a matching model of college admissions with heterogeneous colleges. Academic achievement is exogenous, and the analysis focuses on the role of information frictions within the market (e.g., noisy signals of student ability) and the strategic behavior of colleges in setting admissions standards. Our framework is a frictionless matching market, but academic achievement is endogenous. In that sense, our work and Chade, Lewis, and Smith [15] may be considered complementary for understanding the role of market forces in college admissions.

There is also a large theoretical literature on the topic of affirmative action. Although many of these papers make points related to ours, answering our research questions would be impossible without a model that includes (1) heterogeneous colleges, (2) heterogeneous student quality, and (3) endogenous human capital accumulation choices by the students. Most of the papers in this literature include one or two of these components, but no prior paper includes all three. There is also a rich empirical literature on the effects of affirmative action programs, and we encourage the interested reader to see the summary provided in Hickman [44].

Prior papers have explored the effect of AA on effort incentives, but existing models exhibit important limitations. Fain [26] and Fu [35] study models in the spirit of all-pay contests with complete information (i.e., ability is ex ante observable) where two students compete for a college seat.⁶ Extrapolating the two-player insights to real-world settings is difficult because the framework implicitly assumes that all minority students, even the most gifted ones, are at a disadvantage to even the least talented non-minorities. Franke [28] extends the contest idea to include more than 2 agents, but at the cost of focusing on a specific form of affirmative action program.

The bilateral matching literature has also touched on incentives under AA. An early example is Coate and Loury [22], which studies both human capital investment and achievement gaps. This paper considers two strategic groups of agents, firms and ex ante

⁶Schotter and Weigelt [69] study a similar setting in the laboratory. Their results suggest that no equity-achievement tradeoff exists.

identical job applicants. Job applicants make a binary choice to either become qualified at some cost or remain unqualified given a privately known cost of becoming qualified, and the firms then observe a noisy signal of the potential employee's choice and assign the applicant to one of two positions. Coate and Loury [22] provides conditions under which discriminatory equilibria exist, analyzes the effects of affirmative action on equilibrium outcomes, and demonstrates that the equilibrium beliefs about the qualifications of minority applications can be worsened under an affirmative action program.

Chan and Eyster [16] focuses on the effect of affirmative action bans on a single school when admission can be conditioned on student traits correlated with race. Epple et al. [25] analyzes a similar question, but considers a set of vertically differentiated colleges. Both papers describe how colleges bias their admissions policy to encourage diversity. These papers assume student quality is fixed and exogenous, and so necessarily cannot say much about the general equilibrium effect of the admission policy changes on student incentives. Fryer et al. [32] partially addresses student incentives by including a binary effort choice in the spirit of Coate and Loury [21], but Fryer et al. [32] simplifies the setting by assuming colleges are homogenous.

Fryer [30] touches on our analysis of the equivalence of quota and admissions preference schemes. Fryer [30] studies a model of workplace affirmative action wherein firms that wish to maximize profit are subject to a goal for minority hiring imposed by the government and enforced by an auditor. Fryer [30] finds that firms facing a pool of applicants with few minorities will act as if they are subject to a quota on the number of minorities they must hire, which the author argues implies an equilibrium equivalence between quota and hiring preference systems. In our setting the students are the strategic actors, and our equivalence result is in some ways stronger - not only is the racial balance at colleges in the two systems the same, but the endogenous HC choices of the students is identical across mechanisms.

Finally, our methodology analyzes approximate equilibria played by a large number of agents. Due to the broad scope of this literature, we provide only a brief survey and a sample of the important papers related to the topic. Early papers focused on conditions under which game-theoretic models could be used as strategic microfoundations for general equilibrium models (e.g., Hildenbrand [45] and [46], Roberts and Postlewaite [63], Otani and Sicilian [61], and Jackson and Manelli [49]). Other early papers focused on conditions under which generic games played by a finite number of agent approach some limit game played by a continuum of agents (e.g., Green [39] and [40], Sabourian [66]). A more recent branch of this literature applies these ideas to simplify the analysis of large markets and mechanisms with an eye to real-world applications (e.g., Swinkels [73]; Cripps and Swinkels [23]; McLean and Postlewaite [56]; Budish [11]; Kojima and

Pathak [53]; Fudenberg, Levine and Pesendorfer [33]; Weintraub, Benkard and Van Roy [75]; Krishnamurthy, Johari, and Sundarajan [51]; and Azevedo and Leshno [5]).⁷

Of these papers on approximate equilibria and large games, we would like to single out the contemporaneously developed Olszewski and Siegel [59] as particularly relevant. Olszewski and Siegel [59] uses the limit of a sequence of games played by a finite number of agents to prove that in large contests the outcome is approximately deterministic and assortative for very general prize and agent type distributions. Even though Olszewski and Siegel [59] does not define or study a limit game (as we do), they can use their results to characterize the equilibria in quasi-linear settings. Our goal is to develop limit games played by a continuum of agents that can be used for empirical estimation and counterfactuals as well as theoretical studies, and it is not clear how useful the results of Olszewski and Siegel [59] are for characterizing equilibria outside of the quasi-linear setting. Finally, the productive human capital setting we study as our benchmark and the noisily observed human capital extension are outside of their model. That being said, Olszewski and Siegel [60] skillfully use this framework to study the costs and benefits of coarsening the measures of the performance of students within a contest with an eyes towards exploring the precision of grade measurements.

3. THE FINITE MODEL

We model the market as a Bayesian game where the players are high school students characterized by an observable demographic classification—minority or non-minority—and a privately-known cost type that governs HC production. College seats are allocated to students according to a mechanism that is a function of the students' HC choices and demographic classification. A student's ex-post payoff is the utility derived from enrolling at a given college with her acquired human capital minus her investment cost.

In this section we lay out the model when the number of students and colleges are finite. Although we spend most of the paper working with a limit approximation of this model, the finite model and the limit approximation share the same underlying primitives described in this section (with the exception of the number of players).

3.1. Agents, Actions, and Payoffs. We denote the set of colleges $\mathcal{P}_{\mathcal{K}} = \{p_1, p_2, \dots, p_K\}$, where $p_k \in [\underline{p}, \bar{p}] \subseteq \mathbb{R}_+$ denotes the quality level of the k^{th} college. We denote the k^{th} order statistic by $p(k : K)$ so that $\min_k \{\mathcal{P}_{\mathcal{K}}\} = p(1 : K)$ and $\max_k \{\mathcal{P}_{\mathcal{K}}\} = p(K : K)$. Since colleges have multiple seats of presumably equal quality in reality, this means that there

⁷There also exists a literature on the relationship between large finite and nonatomic games that focuses on games of complete information and does not emphasize the use of nonatomic games as a framework for analyzing equilibria (examples include Housman [47], Khan and Sun [52], Carmona [12], and Carmona and Podczeck [13], Yang [76] and [14] amongst others). Kalai [50] studies large games show the equilibria of finite games are robust to modifications of the game form.

will be elements of $\mathcal{P}_{\mathcal{K}}$ that have the same value. The colleges are passive, meaning each college accepts the students assigned to that college through the admissions contest.

The set of all students is denoted $\mathcal{K} = \{1, 2, \dots, K\}$, but there are two demographic subgroups, $\mathcal{M} = \{1, 2, \dots, K_{\mathcal{M}}\}$ (minorities) and $\mathcal{N} = \{1, 2, \dots, K_{\mathcal{N}}\}$ (non-minorities), where $K_{\mathcal{M}} + K_{\mathcal{N}} = K$ and the demographics of each student is observable.⁸ Each agent has a privately-known cost type $\theta \in [\underline{\theta}, \bar{\theta}] \subset \mathbb{R}_{++}$ that is drawn from group-specific distributions, $F_i(\theta)$, $i \in \{\mathcal{M}, \mathcal{N}\}$. For convenience, we denote the unconditional type distribution for the overall population by $F_{\mathcal{K}}(\theta) = \frac{1}{K} [K_{\mathcal{M}}F_{\mathcal{M}} + K_{\mathcal{N}}F_{\mathcal{N}}]$. The reader should assume throughout that high values of θ are associated with students that have a high cost of accruing human capital.⁹

Each student's strategy space, $\mathcal{S} = [\underline{s}, \infty) \subset \mathbb{R}_{++}$, is the set of HC levels that can be chosen, and each students' choice of HC is observable to the colleges (e.g., through a standardized examination).¹⁰ Human capital \underline{s} is the minimum level required to participate in the market. In the current context, this would be minimum literacy and numeracy thresholds required to attend college. In skilled labor markets \underline{s} might represent a minimum level of education to participate in the market.

Agents value both college quality and HC. The gross match utility derived from being placed at college k for a student with type θ and HC s relative to not attending college is $U(p_k, s, \theta)$. In order to acquire HC $s \in \mathcal{S}$, an agent must incur a cost $C(s, \theta)$, which depends on both her unobservable type and her HC investment level. The total utility for a student of type θ that chooses human capital level s and is assigned to college k is

$$U(p_k, s, \theta) - C(s, \theta)$$

3.2. Allocation Mechanisms. We now describe the contest that allocates students to colleges. We consider color-blind (cb), quota (q), and admissions preference (ap) systems for college assignment. Letting s_i denote student i 's human capital level and \mathbf{s}_{-i} the vector of all other players' actions, we let $P_j(\cdot, \mathbf{s}_{-i}) : \mathcal{S} \rightarrow \mathcal{P}_{\mathcal{K}}$, $j \in \{\mathcal{M}, \mathcal{N}\}$, be an assignment mapping that describes the college to which student i is assigned given each possible HC choice. Note that we have deliberately allowed the assignment mapping to depend on

⁸The assumption that there are two groups is not restrictive. Results for the two-group case extend straightforwardly to the case with $L > 2$ groups.

⁹Costs can arise in various ways: they could come from a labor-leisure tradeoff, where θ indexes one's preference for leisure; they could represent psychic costs, indexed by θ , involved in exerting effort to learn new concepts, where the more able students learn with the least effort; or costs could be interpreted as monetary investment required for study aides (e.g., computers, tutors, and private education), where θ represents the severity of the budget constraint that determines one's consumption-investment tradeoff.

¹⁰In our application we prove that student types generically choose pure actions in equilibrium. In the finite game, the definition of a mixed strategy is standard. In the continuum game, the analog of mixed strategy is a distributional strategy, which was defined in Milgrom and Weber [58].

student i 's demographic classification to reflect potential discrimination between members of the two groups. The ex post payoff for student i is then

$$\Pi_j^r(s_i, \mathbf{s}_{-i}; \theta) = U\left(P_j^r(s_i, \mathbf{s}_{-i}), s_i, \theta_i\right) - C(s_i, \theta_i), r \in \{cb, q, ap\} \text{ and } j \in \{\mathcal{M}, \mathcal{N}\}$$

The *color-blind* admission rule involving no demographic discrimination is represented by the following assignment mapping:

$$(1) \quad P_{\mathcal{M}}^{cb}(s_i, \mathbf{s}_{-i}) = P_{\mathcal{N}}^{cb}(s_i, \mathbf{s}_{-i}) = P^{cb}(s_i, \mathbf{s}_{-i}) = \sum_{k=1}^K p(k : K) \mathbb{1}[s_i = s(k : K)].$$

In the above expression, $\mathbb{1}$ is an indicator function equaling 1 if its argument is true and 0 otherwise. Below we prove that lower cost types choose higher levels of HC, so P^{cb} yields a positive assortative matching between student type and college (i.e., better students with lower θ values match with colleges with higher p).

A *quota* is the practice of reserving seats for each demographic group. Within the current modeling environment, this is equivalent to reserving a set of $K_{\mathcal{M}}$ seats for minorities. Given the reserved seats, assignment occurs via a separate contest for each demographic group that yields an assortative assignment within each group.

Let $\mathcal{P}_{\mathcal{M}} = \{p_{\mathcal{M}1}, p_{\mathcal{M}2}, \dots, p_{\mathcal{M}K_{\mathcal{M}}}\}$ and $\mathcal{P}_{\mathcal{N}} = \{p_{\mathcal{N}1}, p_{\mathcal{N}2}, \dots, p_{\mathcal{N}K_{\mathcal{N}}}\}$ denote the sets of seats reserved for minorities and non-minorities, respectively, and let $\mathbf{s}_{\mathcal{M}} = \{s_{\mathcal{M}1}, s_{\mathcal{M}2}, \dots, s_{\mathcal{M}K_{\mathcal{M}}}\}$ and $\mathbf{s}_{\mathcal{N}} = \{s_{\mathcal{N}1}, s_{\mathcal{N}2}, \dots, s_{\mathcal{N}K_{\mathcal{N}}}\}$ denote the group-specific human capital profiles. Then a quota assignment mapping is represented by the functions

$$(2) \quad \begin{aligned} P_{\mathcal{M}}^q(s_i, \mathbf{s}_{-i}) &= \sum_{m=1}^{K_{\mathcal{M}}} p_{\mathcal{M}}(m : K_{\mathcal{M}}) \mathbb{1}[s_i = s_{\mathcal{M}}(m : K_{\mathcal{M}})], \text{ and} \\ P_{\mathcal{N}}^q(s_i, \mathbf{s}_{-i}) &= \sum_{n=1}^{K_{\mathcal{N}}} p_{\mathcal{N}}(n : K_{\mathcal{N}}) \mathbb{1}[s_i = s_{\mathcal{N}}(n : K_{\mathcal{N}})]. \end{aligned}$$

An *admission preference* system allows the students to compete against all of the other students, but the human capital choices of the members of each group are treated differently. In practice, many American admissions committees are thought to treat observed minority applicants' SAT scores (a commonly used measure of HC) as if they were actually higher when evaluating them against their non-minority competitors.¹¹ More formally, an admission preference is a markup function $\tilde{S} : \mathcal{S} \rightarrow \mathbb{R}_+$ through which minority output is passed to produce a set of transformed HC levels, $\tilde{\mathbf{s}} = \{s_{\mathcal{N}1}, \dots, s_{\mathcal{N}K_{\mathcal{N}}}, \tilde{S}(s_{\mathcal{M}1}), \dots, \tilde{S}(s_{\mathcal{M}K_{\mathcal{M}}})\}$,

¹¹There has been a fair amount of empirical research estimating a substantial average admission preference for minorities at elite American colleges; e.g., Chung, Espenshade and Walling [20] and Chung and Espenshade [19]. Hickman [44] employs a similar empirical measure for the aggregate US college market and finds evidence of a substantial admission preference even at lower-ranked colleges.

and allocations are given by the following group-specific functions:

$$(3) \quad \begin{aligned} P_{\mathcal{M}}^{ap}(s_i, \mathbf{s}_{-i}) &= \sum_{k=1}^K p(k : K) \mathbb{1} \left[\tilde{S}(s_i) = \tilde{s}(k : K) \right], \text{ and} \\ P_{\mathcal{N}}^{ap}(s_i, \mathbf{s}_{-i}) &= \sum_{k=1}^K p(k : K) \mathbb{1} [s_i = \tilde{s}(k : K)]. \end{aligned}$$

Regardless of whether admissions are color-blind or follow some form of AA, ties between competitors are assumed to be broken randomly.

3.3. Model Assumptions. We now outline a series of assumptions on our model primitives. The assumptions serve three goals:

- (1) Establish the existence of a monotone equilibrium
- (2) Justify the use of a centralized, assortative matching structure
- (3) Insure the model is sufficiently well-behaved that our limit approximation is valid

We highlight how the assumptions tie into goals (1) and (2) and defer discussion of (3) until the next section.

Assumption 1. For each $(\theta, s) \in [\underline{\theta}, \bar{\theta}] \times \mathbb{R}_+$, $C_s(s, \theta) > 0$, $C_\theta(s, \theta) > 0$, and $C_{ss}(s, \theta) > 0$

Assumption 2. $U_p(p, s, \theta) > 0$, $U_s(p, s, \theta) \geq 0$, $U_\theta(p, s, \theta) \leq 0$, and $U_{ss}(p, s, \theta) \leq 0$

Assumption 1 states that costs are strictly increasing in human capital level s and cost type θ . Moreover, the cost function is convex in s for any given θ . Assumption 2 states that utility is differentiable, strictly increasing in college quality p , weakly increasing and concave in human capital level s , and weakly decreasing in cost type θ . These assumptions imply that the individual decision problems have global maximums.

Assumption 3. $U(\underline{p}, \underline{s}, \bar{\theta}) - C(\underline{s}, \bar{\theta}) = 0$ and $\arg \max_s U(\underline{p}, s, \bar{\theta}) - C(s, \bar{\theta}) \leq \underline{s}$

Assumption 3 is a boundary condition for our model. First, the assumption requires that the lowest type of student is indifferent between participating in the college admissions contest and not attending college, which normalizes the utility of not attending college to 0. This has the benefit of allowing us to interpret $U(p, s, \theta) - C(s, \theta)$ as the college premium of the students. Second, the assumption demands that the minimally qualified student who chooses to attend college does not have an interest in acquiring more HC, which is supported in the data we use to calibrate our model in section 6.

Assumption 4. There exists \bar{s} such that $U(\bar{p}, \bar{s}, \underline{\theta}) - C(\bar{s}, \underline{\theta}) < U(\underline{p}, \underline{s}, \underline{\theta}) - C(\underline{s}, \underline{\theta})$

Assumption 4 requires that there exist a human capital level so large that even the lowest cost type, the type that gets the largest value from human capital and has the lowest cost for acquiring human capital, would rather not invest in human capital at all and be assigned to the worst school. This implies that we can limit our analysis to human capital levels within $s \in [\underline{s}, \bar{s}]$. Unless otherwise stated, we simply let $\mathcal{S} = [\underline{s}, \bar{s}]$.

Assumption 5. $U_{ps}(p, s, \theta) \geq 0$ and $U_{p\theta}(p, s, \theta) \leq 0$

Assumption 5 requires complementarity between student HC, college quality, and student type. This assumption implies that positive assortative matching is efficient, which helps justify our use of the centralized rank-order mechanisms to model the market.

Assumption 6. $U_{s\theta}(p, s, \theta) \leq 0$ and $C_{s\theta}(s, \theta) > 0$

Assumption 6 states that marginal benefits of HC are decreasing and marginal costs of HC are increasing in a student's type. Assumptions 5 and 6 are key for existence of a monotone pure-strategy equilibrium.

Assumption 7. $F_{\mathcal{M}}(\theta)$ and $F_{\mathcal{N}}(\theta)$ have continuous and strictly positive densities $f_{\mathcal{M}}(\theta)$ and $f_{\mathcal{N}}(\theta)$ on a common support $[\underline{\theta}, \bar{\theta}]$.

Assumption 7 is a regularity condition on the type distributions.

We require the following assumption on the markup functions to prove our approximation result for the admissions preference system. The assumption bounds the marginal markup applied to minority student human capital choices, which helps insure that minority student utility functions are continuous in the limit game.

Assumption 8. $\tilde{S}(\underline{s}) = \underline{s}$ and there exists $\lambda_1, \lambda_2 \in (0, \infty)$ such that for all $s \in \mathcal{S}$ we have

$$\lambda_2 > \tilde{S}'(s) > \lambda_1$$

Assumption 8 makes two substantive restrictions. First, it requires that the worst colleges treat minority and nonminority students on a level playing field. From an empirical perspective, the worst colleges are almost nonselective, which entails treating all students equally. Second, the assumption requires that the admissions preference schemes of colleges of similar quality are similar. From a technical perspective, this assumption is not without loss of generality, but it is necessary to prove that the equilibria of the limit game approximate the equilibria of the limit game. In the end, this is an assumption that must be (and is) supported by the data.

In our model the agents' types are private information, and the agents choose their human capital level given knowledge of the number of competitors from each group $K_{\mathcal{M}}$ and $K_{\mathcal{N}}$, the distribution of student types $F_{\mathcal{M}}$ and $F_{\mathcal{N}}$, the equilibrium strategies, the set of college seats $\mathcal{P}_{\mathcal{K}}$, and the admission rule P_j^r , $r \in \{cb, q, ap\}$ and $j \in \{\mathcal{M}, \mathcal{N}\}$. A Bayes-Nash equilibrium of the game $\Gamma(K_{\mathcal{M}}, K_{\mathcal{N}}, F_{\mathcal{M}}, F_{\mathcal{N}}, \mathcal{P}_{\mathcal{K}})$ is a set of HC accumulation strategies $\sigma_i^r : [\underline{\theta}, \bar{\theta}] \rightarrow \mathbb{R}_+$, $i \in \{1, \dots, K\}$, that generates optimal choices of human capital given that all other agents follow their equilibrium strategies. Note that in our model "monotone" means *decreasing* in type as high θ values imply high costs (and hence low HC choices).

Theorem 1. *In the college admissions game $\Gamma(K_{\mathcal{M}}, F_{\mathcal{M}}, K_{\mathcal{N}}, F_{\mathcal{N}}, \mathcal{P}_{\mathcal{K}})$ with $r \in \{cb, q, ap\}$, under assumptions 1–8 there exists a monotone pure-strategy equilibrium. Moreover, any equilibrium of the game must be strictly monotone with almost every type using pure strategies.*

4. THE LIMIT GAME

From the law of large numbers, we know that as the market becomes large (i.e., as $K \rightarrow \infty$), the distribution of college qualities and realized student types approaches the population distribution almost surely. Intuition suggests if we compute an equilibrium of a limit model featuring a continuum of students and schools with type distribution exactly matching the population distributions, then the equilibrium of this limit model ought to provide a good description of the outcomes in games with a sufficiently large, but finite, set of players.

To see how this simplifies the student’s problem (and as a result, our analysis), consider the plight of a college applicant in the United States. Do would-be college students go to elaborate lengths to determine who else is applying, where those students are applying, and what the other students’ qualifications are? Of course not - to determine whether an application is likely to be accepted, the would-be college student can simply look at data on the grades and SAT scores of currently enrolled students. In our model, this is akin to knowing the equilibrium mapping between human capital levels and school assignments.

We have repeatedly suggested that the equilibria of the limit game are easy to compute, which can be interpreted in two ways. First (and we think most importantly), the equilibria of the limit game are computed in a way that reflects the decision process described in the paragraph above. In other words, a student can discover his or her optimal action in the limit game through reasoning that we believe is typical of real-life behavior, which we think supports the plausibility of the limit model. Second, even using modern algorithms, it is difficult to numerically compute the equilibrium of the finite model when K is large. Our limit model can be used to compute counterfactual contest outcomes. In either case, our challenge is to prove that an equilibrium of the limit game actually does approximate an equilibrium of the more realistic finite agent game when K is large.

Much of the underlying mechanics of the convergence of the finite games to the relevant limit model are the same across the color-blind, admissions preference, and quota games. For each type of college assignment game we consider a sequence of finite games denoted $\{\Gamma(K_{\mathcal{M}}, F_{\mathcal{M}}, K_{\mathcal{N}}, F_{\mathcal{N}}, \mathcal{P}_{\mathcal{K}})\}_{K_{\mathcal{N}}+K_{\mathcal{M}}=2}^{\infty}$. We assume that $\frac{K_{\mathcal{M}}}{K} \rightarrow \mu \in (0, 1)$ as $K \rightarrow \infty$, which implies that μ is the asymptotic mass of the minority group.¹² We let $F_{\mathcal{P}}^K(p)$ denote the distribution of college qualities in the K agent game, and we assume that there is a

¹²Although we assume throughout that the convergence is deterministic, one can think of the agents in the finite games as being created by nature by assigning each agent to group \mathcal{M} with probability $\mu \in (0, 1)$, after which nature draws a cost type for the student from the corresponding distribution.

cumulative distribution function (CDF) $F_{\mathcal{P}}(p)$ such that

$$(4) \quad \lim_{K \rightarrow \infty} \sup_{p \in [p, \bar{p}]} \left\| F_{\mathcal{P}}^K(p) - F_{\mathcal{P}}(p) \right\| = 0$$

Our limit game, which we now define, uses many of the same economic primitives as the finite models. The utility function, $U(p, s, \theta) - C(s, \theta)$, is the same in both the finite game and the limit model. The set of pure actions for the students continues to be the set of HC levels \mathcal{S} . We focus on pure actions in our analysis, and this is largely without loss of generality as Theorem 2 proves that almost all types of agents have a strict preference for a unique action in equilibrium.¹³ The main difference between the finite and limit games is, unsurprisingly, the number of students and colleges. In the limit game there is a measure μ continuum of minority students with types distributed exactly as $F_{\mathcal{M}}$ and a measure $1 - \mu$ continuum of non-minority students with types distributed exactly as $F_{\mathcal{N}}$. Finally, there is a measure 1 continuum of college seats distributed exactly as $F_{\mathcal{P}}$. In order to describe the limit equilibria using an ODE, we must make the following regularity assumption on $F_{\mathcal{P}}$.

Assumption 9. $F_{\mathcal{P}}(p)$ has a continuous density $f_{\mathcal{P}}(p)$.

Equation 4 assumes that as K grows we add colleges to the market. We do not require that each college have a single seat or that the colleges even be the same size. Equation 4 and assumption 9 together require that the size of each college divided by K and the number of colleges of each quality level divided by K both vanish as $K \rightarrow \infty$.

The description of the affirmative action systems in the limit model is significantly more transparent than in the finite game. In the following subsections, we address the color-blind, quota, and admission preference games separately. In each subsection we describe the assignment mapping in the limit model and use the mapping to describe the equilibrium strategy in each game. In Section 4.4 we provide conditions under which there exists an essentially unique PSNE of the limit game. We use the notation $G_j^r(s), j \in \{\mathcal{M}, \mathcal{N}\}$ and $r \in \{cb, q, ap\}$, to denote the equilibrium distributions of HC choices. We use $\psi_j^r, j \in \{\mathcal{M}, \mathcal{N}\}$, to denote the inverse of the equilibrium strategy.

The highlight of the following sections is a simple description of the equilibrium for each form of admissions through an ordinary differential equation (ODE). These descriptions have three purposes. First, since the ODEs provide a tight description of the possible equilibria for almost all types of agents, the ODEs are crucial for proving that the equilibria are essentially unique (Theorem 2). Second, the ODE descriptions are essential for defining the optimal control problems we solve to find the second-best college contest

¹³Defining mixed strategies in the limit game are difficult due to problems defining a continuum of random variables. In games wherein mixed strategies are relevant, they are often defined using a measure over the type and action space, where the distribution over the actions conditional on a particular type is the analog of a mixed strategy in a finite game.

(Section 6). Third (and finally), the ODEs enable easy estimation of the model, although demonstrating this is outside of the scope of this paper.

4.1. Color-blind Admissions Game. We denote the endogenous distribution of human capital levels chosen by the students as $G_{\mathcal{K}}^{cb}(s)$. Since the color-blind admissions system results in an assortative match (higher values of HC match with high college qualities), we can describe the match by mapping quintiles of the HC distribution to quintiles of the school quality distribution. With this in mind, we can describe the match of students to colleges as:

$$\begin{aligned}
 P_{\mathcal{M}}^{cb}(s) &= P_{\mathcal{N}}^{cb}(s) = P^{cb}(s) = F_{\mathcal{P}}^{-1} \left(G_{\mathcal{K}}^{cb}(s) \right) \\
 (5) \qquad \qquad &= F_{\mathcal{P}}^{-1} \left(\mu G_{\mathcal{M}}^{cb}(s) + (1 - \mu) G_{\mathcal{N}}^{cb}(s) \right) \\
 &= F_{\mathcal{P}}^{-1} \left(1 - \mu F_{\mathcal{M}} \left(\psi^{cb}(s) \right) - (1 - \mu) F_{\mathcal{N}} \left(\psi^{cb}(s) \right) \right).
 \end{aligned}$$

The intuition is simple: quantiles of the population HC distribution $G_{\mathcal{K}}^{cb}(s)$ are mapped into the corresponding quantiles of the distribution $F_{\mathcal{P}}$. Since the students are individually measure 0, deviations by a single player do not affect the assignment of any other student. Combined with the fact that the color-blind system treats students of different demographic groups identically, we conclude that the assignment mapping P^{cb} need not be player specific.

We now turn to describing the equilibrium of the color-blind limit game. Given that the equilibrium will, in the end, be assortative, we can write the endogenous assignment function as a function of agent type as follows:

$$(6) \qquad P_{\mathcal{M}}^{cb}(\theta) = P_{\mathcal{N}}^{cb}(\theta) = F_{\mathcal{P}}^{-1} \left(1 - \mu F_{\mathcal{M}}(\theta) - (1 - \mu) F_{\mathcal{N}}(\theta) \right) = F_{\mathcal{P}}^{-1} \left(1 - F_{\mathcal{K}}(\theta) \right)$$

If we describe the agent's problem in revelation mechanism form, then the decision problem reduces to:

$$\max_{\hat{\theta}} U \left(P^{cb}(\hat{\theta}), \sigma^{cb}(\hat{\theta}), \theta \right) - C \left(\sigma^{cb}(\hat{\theta}), \theta \right)$$

Manipulating the first order condition for this problem¹⁴ and using the fact that in equilibrium we have $\hat{\theta} = \theta$ yields the following differential equation for investment:

$$\begin{aligned}
 (7) \qquad \frac{d\sigma^{cb}(\theta)}{d\theta} &= - \frac{U_p \left(P^{cb}[\sigma^{cb}(\theta)], \sigma^{cb}(\theta), \theta \right) \cdot f_{\mathcal{K}}(\theta)}{f_{\mathcal{P}} \left(F_{\mathcal{P}}^{-1} \left(1 - F_{\mathcal{K}}(\theta) \right) \right) \cdot \left(C_s \left(\sigma^{cb}(\theta), \theta \right) - U_s \left(P^{cb} \left(\sigma^{cb}(\theta) \right), \sigma^{cb}(\theta), \theta \right) \right)} \\
 \sigma^{cb}(\bar{\theta}) &= \underline{s} \quad (\text{boundary condition}).
 \end{aligned}$$

The boundary condition comes from the fact that a player of type $\bar{\theta}$ will always be matched with the lowest seat in a monotone equilibrium, so she cannot do better than to

¹⁴Importantly, this implies that the local incentive compatibility conditions are already "built in" to the differential equations. What remains is to show global incentive compatibility.

simply choose HC level \underline{s} . Given the assumptions on the model primitives, the solution to Equation 7 is strictly decreasing.

4.2. Quota Game. The empirical CDF of seats allocated to group $j \in \{\mathcal{M}, \mathcal{N}\}$ in the K -agent game is denoted Q_j^K . We assume that there exists a distribution of seats $Q_j(p)$ such that:

$$\lim_{K \rightarrow \infty} \sup_{p \in [\underline{p}, \bar{p}]} \|Q_j^K(p) - Q_j(p)\| = 0$$

In the limit quota game a measure μ of minority students with types exactly distributed as $F_{\mathcal{M}}$ compete in a contest for a pool of seats exactly distributed as $Q_{\mathcal{M}}$. Similarly, a measure $1 - \mu$ of non-minority students with types exactly distributed as $F_{\mathcal{N}}$ compete in a separate contest for a pool of seats exactly distributed as $Q_{\mathcal{N}}$. The measures $Q_{\mathcal{M}}$ and $Q_{\mathcal{N}}$ are subject to the following feasibility constraint:

$$\text{For all } p \text{ we have } \mu Q_{\mathcal{M}}(p) + (1 - \mu)Q_{\mathcal{N}}(p) = F_{\mathcal{P}}(p)$$

Finally, we assume that the quota measures admit a density.

Assumption 10. $Q_j(p)$, $j \in \{\mathcal{M}, \mathcal{N}\}$, admits a density $q_j(p)$ on $[\underline{p}, \bar{p}]$.

Each demographic group's contest results is an assortative match of types to the college seats allocated to that contest. These distinct contests yield group-specific assignment mappings of the form:

$$(8) \quad P_j^q(s) = Q_j^{-1}(G_j^q(s)) = Q_j^{-1}(1 - F_j(\psi_j^q(s))), \quad j \in \{\mathcal{M}, \mathcal{N}\}.$$

for values of s such that $Q_j^{-1}(G_j^q(s))$ is well defined.¹⁵ In cases where $Q_j^{-1}(G_j^q(s))$ is not well defined, we let $P_j^q(s) = \sup\{P_j^q(s') : s' < s\}$. As in the color-blind case, the quantiles of the group-specific human capital distributions are mapped into the corresponding quantiles of Q_j . The following differential equation describes the equilibrium when Q_j has a connected support.

$$(9) \quad \frac{d\sigma_j^q(\theta)}{d\theta} = - \frac{U_p(P_j^q(\sigma_j^q(\theta)), \sigma_j^q(\theta), \theta) \cdot f_j(\theta)}{q_j(Q_j^{-1}(1 - F_j(\theta))) \cdot (C_s(\sigma_j^q(\theta), \theta) - U_s(P_j^q(\sigma_j^q(\theta)), \sigma_j^q(\theta), \theta))},$$

$$\sigma_j^q(\bar{\theta}) = \underline{s} \quad (\text{boundary condition}).$$

When Q_j does not have a connected support, then there will be jumps in the equilibrium strategies when $P_j^q(\sigma_j^q(\theta))$ encounters the left edge of a gap in the support. The interested reader is referred to Online Appendix B for a description of how to identify the location and size of the jumps. Between these jumps, Equation 9 describes the equilibrium strategy.

¹⁵If we allow Q_j to have a disconnected support, then Q_j need not be strictly monotone and the inverse will not exist.

4.3. Admissions Preference Game. As in the finite-agent model, an admission preference rule is modeled as a markup function $\tilde{S} : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ and seats are matched assortatively with transformed HC. In other words, minorities are repositioned ahead of non-minority counterparts with an investment of $\tilde{S}(s)$ or less. The limiting assignment mapping for group \mathcal{M} is:

$$(10) \quad \begin{aligned} P_{\mathcal{M}}^{ap}(s) &= F_{\mathcal{P}}^{-1} \left((1 - \mu)G_{\mathcal{N}} \left(\tilde{S}(s) \right) + \mu G_{\mathcal{M}}(s) \right) \\ &= F_{\mathcal{P}}^{-1} \left(1 - \left((1 - \mu)F_{\mathcal{N}} \left(\psi_{\mathcal{N}}^{ap} \left(\tilde{S}(s) \right) \right) + \mu F_{\mathcal{M}} \left(\psi_{\mathcal{M}}^{ap}(s) \right) \right) \right) \end{aligned}$$

and the limiting assignment mapping for group \mathcal{N} is given by:

$$(11) \quad \begin{aligned} P_{\mathcal{N}}^{ap}(s) &= F_{\mathcal{P}}^{-1} \left((1 - \mu)G_{\mathcal{N}}(s) + \mu G_{\mathcal{M}} \left(\tilde{S}^{-1}(s) \right) \right) \\ &= F_{\mathcal{P}}^{-1} \left(1 - \left((1 - \mu)F_{\mathcal{N}} \left(\psi_{\mathcal{N}}^{ap}(s) \right) + \mu F_{\mathcal{M}} \left(\psi_{\mathcal{M}}^{ap} \left(\tilde{S}^{-1}(s) \right) \right) \right) \right) \end{aligned}$$

The intuition for the above expressions is similar as before: limiting mechanisms map the quantiles of a distribution into the corresponding college seat quantiles. For non-minorities, it is a mixture of the distributions of non-minority HC and subsidized minority HC. For minorities, it is a mixture of the distributions of minority HC and de-subsidized non-minority HC.

Unlike the color-blind or quota case, it is not possible to describe which kind of student obtains each seat in an admissions preference scheme without first solving for the equilibrium. This feature of the admissions preference mechanism makes it significantly harder to work with than the other two schemes. However, we prove in Section 5 that the admissions preference and quota schemes are outcome equivalent - for any admissions preference markup function one can describe a quota scheme that generates the same school assignment and equilibrium human capital choices. Because of this equivalence, for the majority of the paper we work with color-blind and quota systems. However, for completeness, we now provide the differential equations describing the admissions

preference equilibrium when \tilde{S} is differentiable and $\tilde{S}(\underline{s}) = \underline{s}$.¹⁶

$$(12) \quad (\psi_{\mathcal{M}}^{ap})'(s) = - \frac{C_s(s, \psi_{\mathcal{M}}^{ap}(s)) - U_s(P_{\mathcal{M}}^{ap}(s), s, \psi_{\mathcal{M}}^{ap}(s))}{U_p(P_{\mathcal{M}}^{ap}(s), s, \psi_{\mathcal{M}}^{ap}(s))} \cdot \frac{f_P(P_{\mathcal{M}}^{ap}(s))}{\mu f_{\mathcal{M}}(\psi_{\mathcal{M}}^{ap}(s))} \\ - \frac{(1-\mu)f_{\mathcal{N}}(\psi_{\mathcal{N}}^{ap}(\tilde{S}(s)))}{\mu f_{\mathcal{M}}(\psi_{\mathcal{M}}^{ap}(s))} (\psi_{\mathcal{N}}^{ap})'(\tilde{S}(s)) \frac{d\tilde{S}(s)}{ds}$$

and

$$(\psi_{\mathcal{N}}^{ap})'(s) = - \frac{C_s(s, \psi_{\mathcal{N}}^{ap}(s)) - U_s(P_{\mathcal{N}}^{ap}(s), s, \psi_{\mathcal{N}}^{ap}(s))}{U_p(P_{\mathcal{N}}^{ap}(s), s, \psi_{\mathcal{N}}^{ap}(s))} \cdot \frac{f_P(P_{\mathcal{N}}^{ap}(s))}{(1-\mu)f_{\mathcal{N}}(\psi_{\mathcal{N}}^{ap}(s))} \\ - \frac{\mu f_{\mathcal{M}}(\psi_{\mathcal{M}}^{ap}(\tilde{S}^{-1}(s)))}{(1-\mu)f_{\mathcal{N}}(\psi_{\mathcal{N}}^{ap}(s))} (\psi_{\mathcal{M}}^{ap})'(\tilde{S}^{-1}(s)) \frac{d\tilde{S}^{-1}(s)}{ds}$$

4.4. Equilibrium Existence. Since the limit game is one of complete information, the relevant equilibrium concept is a Nash equilibrium. Our definition of a Nash equilibrium with a continuum of agents is presented below. Our notation implies that all agents within each group play the same strategy, which Theorem 2 implies must be the case in equilibrium.

Definition 1. $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ is a **group-symmetric Nash equilibrium** of the limit game for system $r \in \{cb, q, ap\}$ if for $j \in \{\mathcal{M}, \mathcal{N}\}$ and all $\theta \in [\underline{\theta}, \bar{\theta}]$

$$\sigma_j(\theta) \in \arg \max_s U(P_j^r(s), s, \theta) - C(s, \theta)$$

given the endogenous $P_j^r(s)$ generated by $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$. The equilibrium is **essentially unique** if in any equilibrium all but a measure 0 set of types take actions as per $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$.

First note that in any equilibrium, the assignment mapping is strictly monotone increasing and admits a countable number of discontinuities. For group-symmetry to be violated, we would require a positive measure of types to have multiple best responses to the assignment mapping. We use the theory of strict monotone comparative statics developed by Edlin and Shannon [24] to show that multiple best responses can only occur when the agent's HC choice places her at a discontinuity in the assignment mapping. Since the assignment mapping has a countable set of discontinuities, this can occur only for a measure 0 set of types (implying group-symmetry).

To prove essential uniqueness we argue that any group-symmetric equilibria must respect the boundary condition $\sigma_j(\bar{\theta})$ and the first order conditions captured by the differential equations describing the equilibrium (Equations 7, 9, and 12). The difficulty we encounter is proving that any discontinuities in the equilibrium strategies must be uniquely defined. In the quota or color-blind system, it is straightforward to prove that

¹⁶ If \tilde{S} is not differentiable or $\tilde{S}(\underline{s}) \neq \underline{s}$, then the equilibrium may involve jumps. The interested reader is referred to Online Appendix B for a description of how to identify the size and location of these jumps.

both the initial condition and any jumps in the equilibrium strategy are uniquely defined. This means the necessarily pure actions of the measure 1 of types that are not at discontinuities in σ_i^q are uniquely defined, which implies group-symmetry and essential uniqueness.

We require stronger conditions on admissions preference systems. It is straightforward to show the existence of an equilibrium, and any equilibrium of the admissions preference game is group symmetric and almost all agents use pure actions. However, we have not discovered a method for proving that the discontinuities are uniquely defined without Assumption 8.

Theorem 2. *The equilibrium of any of our limit game affirmative action systems is essentially unique, almost all of the agents take pure actions, and the strategies are group-symmetric.*

4.5. Approximating the Finite Game with Limit Equilibria. Having defined the equilibria of the limit model using ODEs and proven that the equilibrium thus described exists and is essentially unique, we now argue that the equilibrium of the limit game is a useful approximation of the equilibria in games with a large, but finite, set of players. We use two notions of approximate equilibrium in this paper. Our first definition provides for an approximation in terms of incentives - agents that follow an ε -approximate equilibrium can gain at most ε by deviating. Intuitively, students lose little utility if they base their actions on the easy-to-compute limit game equilibrium strategy.

Definition 2. *Given $\varepsilon > 0$, an ε approximate equilibrium of the K -agent game is a K -tuple of strategies $\sigma^\varepsilon = (\sigma_1^\varepsilon, \dots, \sigma_K^\varepsilon)$ such that for all agents, almost all types θ , and all human capital choices s' we have*

$$U\left(P_j^r(\sigma_i^\varepsilon(\theta), \sigma_i^\varepsilon(\theta)), \sigma_i^\varepsilon(\theta), \theta_i\right) - C(\sigma_i^\varepsilon(\theta), \theta_i) + \varepsilon \geq U\left(P_j^r(s', \sigma_i^\varepsilon(\theta)), s', \theta_i\right) - C(s', \theta_i)$$

A δ -approximate equilibrium provides a close approximation of the actual HC choices of each of the agents regardless of the exact equilibrium played.

Definition 3. *Given $\delta > 0$, a δ -approximate equilibrium of the K -agent game is a K -tuple of strategies $\sigma^\delta = (\sigma_1^\delta, \dots, \sigma_K^\delta)$ such that for any exact equilibrium of the K -agent game $\sigma = (\sigma_1, \dots, \sigma_K)$ we have for all agents and almost all types θ that $\|\sigma_i^\delta(\theta) - \sigma_i(\theta)\| < \delta$.*

Our goal is to prove that the equilibrium of the limit game is a δ -approximate equilibria of admissions games with sufficiently many students. Proving this result amounts to proving that the limit game is continuous in the appropriate sense.

Theorem 3. *Consider any admissions preference game or a quota game where $Q_{\mathcal{M}}$ and $Q_{\mathcal{N}}$ admit strictly positive PDFs over a connected support. Let σ_j^r , $j \in \{\mathcal{M}, \mathcal{N}\}$ and $r \in \{cb, q, ap\}$, denote an equilibrium of the limit game. Under assumptions 1-9 and given $\varepsilon, \delta > 0$, there exists $K^* \in \mathbb{N}$ such that for any $K \geq K^*$ we have that σ_j^r is a ε -approximate equilibrium and a δ -approximate equilibrium of the K -agent game.*

When many students follow the equilibrium strategy of the limit game, then the realized distribution of human capital will (with high probability) be approximately the same as the distributions realized in the limit game. If the student utility functions are continuous, then these small differences have a negligible effect on the agent utility for each possible action (and so the maximum utility changes only slightly). This implies that $(\sigma_{\mathcal{M}}^r, \sigma_{\mathcal{N}}^r)$ is a ε -approximate equilibrium of the K -agent game.

Theorem 3 also implies that every equilibrium of the finite game must be close to the essentially unique equilibrium of the limit game. In order to prove this claim, we need to rule out discontinuities in the utility functions of the agents with respect to s and the distribution of s across the population. Such a discontinuity can arise either through the contest structure or the endogenous equilibrium strategy. Once the model is shown to be sufficiently continuous, we can quickly show that the equilibrium correspondence is upper hemicontinuous in K . In other words, an exact equilibrium of the admissions game with many players must be close to some equilibrium of the limit game. However, it could be the case that there are equilibria of the limit game that are unlike any equilibrium of the finite game (i.e., lower hemicontinuity of the equilibrium correspondence might fail). To rule this out, we use the fact that the limit game has an essentially unique equilibrium to prove that the equilibrium correspondence is in fact continuous and $(\sigma_{\mathcal{M}}^r, \sigma_{\mathcal{N}}^r)$ is a δ -approximate equilibrium.

5. MECHANISM EQUIVALENCE

In this section we make our argument that the quota and admissions preferences systems are outcome equivalent. The notion of equivalence we use implies that not only are the same ratio of minority to non-minority students assigned to each school, but the students at each school choose the same level of human capital under both systems.¹⁷

Theorem 4. $P_j(s) : \mathcal{S} \rightarrow \mathcal{P}, j \in \{\mathcal{M}, \mathcal{N}\}$, is the result of an equilibrium of some quota system if and only if there is an equilibrium of an admissions preference system that also yields these assignment functions and admits the same equilibrium strategies.

The key insight underpinning Theorem 4 is that outcomes and agent incentives are entirely determined by the reduced-form assignment mapping, P_j . Our proof shows through algebraic manipulations that one can convert an admissions preference assignment mapping, P^{ap} , and a markup function for minority student HC, \tilde{S} , into quota system assignment mappings for each group, $P_{\mathcal{N}}^q$ and $P_{\mathcal{M}}^q$. A similar argument is made that one can “transform” quota system assignment mappings into an assignment mapping and a minority HC markup function. The only subtlety is to verify that the result of these

¹⁷We have not proven that any choice of $P_j(s), j \in \{\mathcal{M}, \mathcal{N}\}$, can be implemented by either a quota or an admissions preference scheme. For example, if $P_j(s)$ is strictly decreasing, then it cannot be implemented by any incentive compatible mechanism.

transformations does not violate the feasibility of the quota system or the monotonicity of the minority student HC markup function.

Theorem 4 is useful from a methodological perspective because it shows that there is no loss in generality from focusing solely on outcomes that can be realized using quota systems. Recall that under a quota system the equilibrium assignment of student types to colleges within each group is assortative, which means the only unknown endogenous quantity is the agents' strategies. In an admission preferences system, both the equilibrium human capital choices and the school assignment need to be computed, which makes the admissions preference schemes more difficult to study. The simplicity of the quota system provides a great deal of computational stability to the algorithms used to solve the optimal control problems in Section 6.

Our result bears a resemblance to the equivalence of quotas and tariffs in an international trade context (e.g., Bhagwati [7]), although our setting is complicated by the continuum of heterogeneous "goods" (i.e., college seats) being assigned and the continuum of endogenous "prices" (i.e., human capital levels) required to obtain the goods. Even without the insights from the international trade literature, we do not view it as surprising that the same assignment of student types to colleges can be generated using either type of mechanism. We find it more surprising that the endogenous human capital decisions can also be replicated, and (to the best of our knowledge) there is no analog of this result in the international economics literature. Some insights, such as the breakdown of the equivalence in the presence of aggregate uncertainty, are true both of the quota-tariff equivalence and our college admissions model.

As just hinted, the equivalence of admissions preference and quota schemes relies on the distribution of student types being fixed and known. If there are aggregate shocks to the distribution of student types, the equivalence will no longer hold unless the quota and admissions preference schemes are allowed to be functions of the realized distribution of applicant types. For example, under a quota scheme that is not responsive to the distribution of student types, the set of college seats reserved for minority student remains fixed even in the event that the minority student population is significantly better (or worse) than expected relative to the set of non-minority students. In contrast, an admissions preference scheme allows an unusually high quality minority applicant cohort to be allocated an unusually large number of seats at excellent schools. Large aggregate shocks in the distribution of undergraduate applicants seems unlikely, but it is easy to imagine aggregate shocks such as economic cycles that would affect the pool of applicants to MBA programs.

From a legal perspective, Theorem 4 throws light on why it has proven so difficult for the U.S. court system to draw a line between constitutionally permissible and impermissible affirmative action systems. The cornerstone of Supreme Court jurisprudence regarding affirmative action is the 1978 case *University of California Regents v. Bakke* [64].

Justice Powell's opinion established that the government has a compelling interest in encouraging diversity in university admissions founded on principles of academic freedom and a university's right to take what actions it feels necessary to provide a high quality education to its students. Given this compelling interest, universities are free to implement affirmative action programs, although these programs must be narrowly tailored and are subject to a rigorous "strict scrutiny" standard of review. In particular, Justice Powell's opinion clearly ruled that quotas violate the U.S. Constitution's 14th amendment's guarantee of equal protection because non-minority students cannot compete for the seats reserved for minority applicants.

The 2003 cases *Gratz et al. v. Bollinger et al.* and *Grutter v. Bollinger et al.* were the first affirmative action cases addressed by the Supreme Court following the ruling in *University of California Regents v. Bakke*. These cases turned on whether the University of Michigan admissions preference schemes are narrowly tailored. The justices in both of these cases looked to the outcomes to judge the extent to which the systems function as de facto quotas (and are hence unconstitutional). For example, in Justice Scalia's dissenting opinion he wrote:

"... the University of Michigan Law School's mystical "critical mass" justification for its discrimination by race challenges even the most gullible mind. The admissions statistics show it to be a sham to cover a scheme of racially proportionate admissions." (Scalia, p. 346 - 347 of *Grutter*)

Theorem 4 implies that attempts to differentiate between unconstitutional quotas and constitutional admissions preferences on the grounds of the outcomes produced will prove futile. The delineation between admission preference and quota schemes must be based on something other than the implemented outcomes.

6. THE WELFARE COST OF COMPETITION

We now use our model to address the welfare cost of the competition for college seats. First, we would like to illustrate the source of the welfare loss due to competition. The limiting payoff for agent type θ with HC s is $\Pi^{cb}(s; \theta) = U(P^{cb}(s), s, \theta) - C(s; \theta)$. Differentiating, we get the following first-order condition:

$$\underbrace{\frac{\partial U}{\partial s}}_{\text{Productive Channel}} + \underbrace{\frac{\partial U}{\partial p} \cdot \frac{dP^{cb}(s)}{ds}}_{\text{Competitive Channel}} = \frac{dC}{ds}$$

The above expression states that the marginal cost of human capital investment (the right-hand side) must be exactly offset by the marginal benefits (the left-hand side), which can be decomposed into two parts. First, there is the direct value accrued to the student of marginal increases to HC level s , represented by the term $\partial U / \partial s$; this is the *productive channel* of investment incentives. There is also the indirect benefit of marginally improving

the college to which the student is assigned. An increase in one's human capital level will improve the college quality at a rate of $dP^{cb}(s)/ds$, and the marginal utility of a change in college quality is $\partial U/\partial p$. The product of these two terms represents the *competitive channel* of investment incentives.

For the moment, suppose types were observable to a benevolent planner that could match students to colleges assortatively and allow them to invest ex post, in which case the first order condition (FOC) would be $U_s(P^{r*}(\theta), s, \theta) = C_s(s, \theta)$ where $P^{r*}(\theta) = F_p^{-1}(1 - F_K(\theta))$. We refer to the outcome generated by the social planner's omniscient assignment and the ex post investments of the students as the *First-Best Outcome*. Since the marginal benefit of accruing human capital is strictly lower in the first-best outcome, clearly the students will accrue lower levels of HC. We summarize this observation in the following observation:

Remark 1. *HC investment for all types below $\bar{\theta}$ in the color-blind admissions scheme strictly exceeds that in the first-best outcome.*

When considering what the second-best solution might look like in a world with incomplete information, one must balance two welfare effects of competition. First, color-blind competition allows the students to reveal their types in an incentive compatible fashion, which is necessary for an efficient, assortative match in an incomplete information setting. Second, the accumulation of human capital merely for the purpose of competing for a better college imposes negative externalities on the other students. If a high cost student increases her HC level to obtain a better college, then every student of lower cost must increase their HC choice as well if they wish to retain their college assignment.

It is not obvious how these forces balance in an incomplete information world. Should the students compete in a color-blind system that insures an assortative match? Or should society seek to minimize the negative externalities by dampening the competitive channel even though we may end up in a nonassortative match? We answer these questions using a calibrated model.

The remaining results we present in this section are numerical solutions of our model conducted using the estimated utility functions and type distributions from Hickman [44] to calibrate our model. We provide a summary of the data sources here, but the interested reader should consult Appendix C for more details on the data and the estimation techniques employed. The analysis of Hickman [44] is conducted using data from the 1995-1996 application year. Hickman [44] uses the US News and World Report college quality index as his metric for college quality, p , and supplements this data with information from the Integrated Postsecondary Education Data Survey, conducted by the US Department of Education, to determine supply of seats within each college. A student's human capital level, s , is represented by the student's SAT score. The probability

of graduating is a function of the college's quality and the median SAT score at the college as provided by The College Board. The average salary 10 years after graduation as a function of SAT and college quality (conditional on graduating) is computed from the Baccalaureate and Beyond survey of individuals that graduated in the 1992 - 1993 academic year conducted by the U.S. Department of Education. The Baccalaureate and Beyond survey collects data on entering college students and follows these students for 10 years post-graduation, which allows us to estimate the relationship between human capital, college placement, and salary 10 years post-graduation. We use the Current Population Survey to estimate the salary growth rate path for the typical college graduate over the course of her lifetime. We combine these data sources with the average salary profile of a college graduate as computed by the Current Population Survey of the U.S. Census Bureau to estimate the net present value of lifetime salary as a function of human capital accrued before college and the college assignment assuming a yearly discount factor of $\delta = 0.98$. All of our estimates were restricted to the population of male individuals in the respective surveys.

For the utility functions we use:

$$\begin{aligned} U(p, s, \theta) &= \rho(p, s) * u(p) \\ \rho(p, s) &= -0.176 + 0.000774s - 0.00000049s^2 + 0.00076ps \\ u(p) &= 40,134p^{0.536} \end{aligned}$$

where ρ represents the probability of graduating from college and u is the net present value of the lifetime college salary premium conditional on graduating. The cost function for the model is

$$C(s, \theta) = \theta e^{0.013(s-\underline{s})}, \underline{s} = 520$$

where a student's θ is inferred from his or her behavior under the status quo college admissions contest.¹⁸

The costs of competition can be interpreted in terms of net present value (NPV) of lifetime salary. When we consider the total effect, we use the statistic that 1,056,580 students enrolled in four year colleges in the fall of 1996 drawn from the Integrated Postsecondary Education System Dataset.

¹⁸All numbers used in this calibrated comparative static exercise were taken from [44], whose identification and estimation strategy applies techniques from the auctions literature pioneered by Guerre, Perrigne, and Vuong [42]. Intuitively, the data contain two main components needed for identification. First, the supply and relative value of each seat on the college market characterize the distribution of gross payoffs on the table before the strategic investment game begins. Second, the distributions of SAT scores characterize the equilibrium level of competition for a given gross payoff. Therefore, one can in principle reverse engineer the private type θ which rationalizes each observed SAT score s (within each race group) as a best response to prevailing market conditions, including level of competition and stakes.

Although it is outside of the scope of this paper to provide a model that endogenizes school quality, it is well known that there are spillovers between students in many contexts that make school quality a function of which students enroll. The spillovers may be a function of student characteristics (e.g., Hoxby [48]) or student effort choices (e.g., Fruewirth [29]). In addition, if we take at face value the briefs filed by the universities in *Regent of the University of California v. Bakke* [64], *Gratz v. Bollinger* [38], and *Grutter v. Bollinger* [41], universities believe that student welfare is directly enhanced by diversity amongst the student body.

Since the first-best outcome, the color-blind contest, and the status quo contests all result in roughly assortative matches,¹⁹ it is plausible that the distribution of college qualities is the same in all three cases even when spillovers are considered. However, the second best contest results in a significantly nonassortative outcome, and we view these estimates as more speculative. Our goal when computing the second-best is to illustrate the tensions between efficiency and fairness and not to compute a specific second-best welfare statistic.

6.1. The Cost of Competition. To estimate the welfare cost of competition we compare the first-best outcome with the color-blind contest. Note that both of these assignments are perfectly assortative. In the first-best assignment, the students' types are known by an omniscient social planner, and the students are assigned to colleges prior to choosing their HC level. In the color-blind match the students' HC level is the tool used to rank and assign the students. The only difference in the outcome is that the students in the color-blind contest are pushed by the competitive channel to accrue more human capital. The *cost of competition* is the average welfare in the color-blind outcome minus the average welfare in the first-best outcome.

Computing the first-best outcome numerically is straightforward. From equation 6 we know the assignment of each type in both the first-best and color-blind counterfactuals is $P(s) = F_{\mathcal{P}}^{-1}(1 - F_{\mathcal{K}}(\theta))$. We compute the optimal HC level in the first-best outcome for each student using a brute-force algorithm to solve:

$$\sigma_{\text{First Best}}(\theta) = \arg \max_s U\left(F_{\mathcal{P}}^{-1}(1 - F_{\mathcal{K}}(\theta)), s, \theta\right) - C(s, \theta)$$

For the color-blind case, we used the estimates of $f_{\mathcal{P}}$ and $f_{\mathcal{K}}(\theta)$ from Hickman [44] and numerically computed the solution to Equation 7, which is the ODE defining the color-blind equilibrium strategy. With the strategies in hand, we then compute the welfare as a function of the agents' types under both counterfactuals. For the college premium for a type θ , we simply used $U\left(F_{\mathcal{P}}^{-1}(1 - F_{\mathcal{K}}(\theta)), \sigma_{\text{First Best}}(\theta), \theta\right)$.

¹⁹The affirmative action scheme used in the status quo economy result in some slight nonassortativity since the type of minority students at any given school is higher than the type of the nonminority student at that school. Given that the affirmative action effects are not too large and the minority students make up a small fraction of the population, the aggregate result is approximately assortative.

The following table presents the average welfare over the population in terms of the net present value of lifetime salary given a yearly discount factor of $\delta = 0.98$. It is straightforward to compute the assortative match between student-type and college quality required by the first-best outcome, numerically compute the efficient level of HC for each student, and then compute the average student utility. The college premium is simply the student match utility in the first-best outcome (i.e., it does not include the cost of HC). Although the color-blind outcome is an assortative match, we must use the ODE description of the students' strategy (Equation 7) to compute the equilibrium HC choices of the students.

	NPV of Future Salary
College Premium	\$738,340
First-Best	\$702,341
Color-blind	\$610,546
Cost of Competition	-\$91,795

For a more granular perspective we have plotted the welfare cost of competition by the percentile of school quality to which those students are assigned. Figure 1 reveals where the burden of the cost of competition falls.

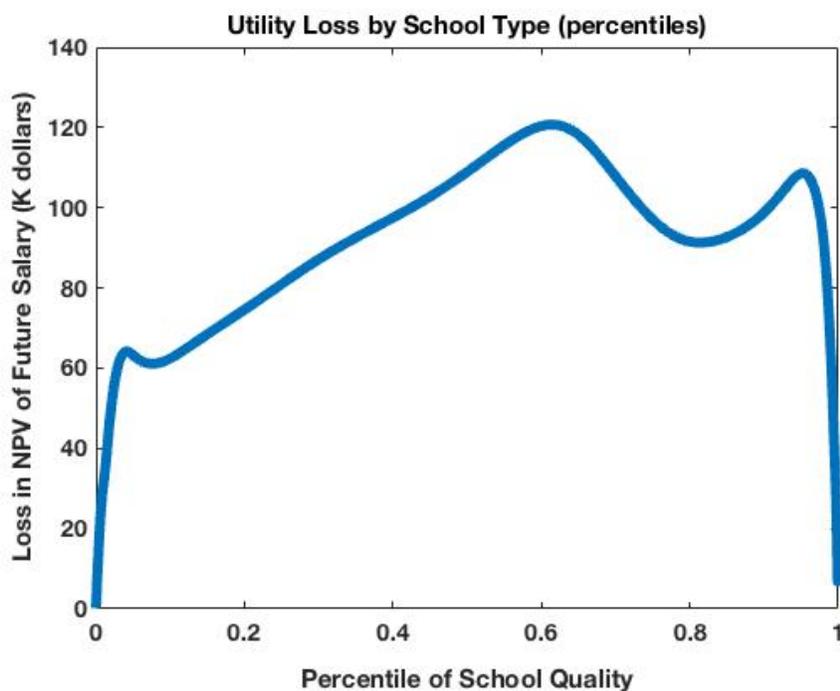


FIGURE 1.

There are two features of note to point out. The initial increase in welfare losses is because students impose negative externalities only on students at better schools. If a

particular student increases his or her choice of human capital, students with lower cost types (i.e., assigned to better schools) must increase their own levels of human capital to retain their placement. The second feature of note is the eventual decline of the welfare losses, which is due to the long tail of students with very low costs of accumulating human capital. These students are naturally inclined, due to their low cost types, to accumulate large levels of human capital and are less adversely affected by the competitive channel.

We would like to close out this section with four observations. First, one should note that the welfare loss of \$91,795 is, in reality, spread across the entire time the student has been accumulating human capital in the 18 years before enrolling in college. Second, when multiplied by the over one million students that enroll in college each year, the total losses are almost \$100 billion per year. Finally, our estimates imply that 3.5 times as much human capital (in terms of NPV of future income) is accumulated per student in the color-blind contest as in the first-best outcome. In this sense, one can conclude that a large fraction of the human capital cost accrued by students is, in essence, wasteful signaling of underlying type.

Finally, we would like comment on the potential role of externalities, which can come from several sources. First, colleges surely place a value on the both the innate ability and the human capital of the students they enroll, which is not included in this model. Second, and relatedly, there are likely to be spillovers between students as a result of student characteristics (e.g., Hoxby [48]) or student effort choices (e.g., Fruewirth [29]). In our model this could be captured by endogenizing a link between college quality (p) and the human capital of the students enrolled at that college. We have not included such a component in our model because it is difficult to see how such a feature could be credibly estimated. Third, students with high levels of human capital are likely to generate positive externalities for society more broadly. Although our model cannot shine much light on the magnitude of these positive externalities, they clearly ought to be weighed against the large costs of competition imposed on young, would-be college students.

6.2. Computing the Second Best. We now compute the second-best college assignment contest to discover what fraction of the welfare gains of the first-best can be recovered by admissions policy changes. The optimal contest design problem takes the form of an optimal control problem. The control variable, $u(p) \in [0, 1]$, represents the fraction of seats at school p that are allocated to minority students. In effect we are solving for an optimal quota system, which is equivalent to, but much more computationally tractable than, computing an optimal admissions preference system (Theorem 4). Because the index variable is the college, p , all of the variables in our problem must be written as functions of p . The state variables of our control problem are the equilibrium strategies

of the students, $\sigma_{\mathcal{M}}(p)$ and $\sigma_{\mathcal{N}}(p)$, and the type of the student from each group that is assigned a seat at college p , $\theta_{\mathcal{M}}(p)$ and $\theta_{\mathcal{N}}(p)$. Our optimal control problem can be written:

$$\max_u \int_{\underline{p}}^{\bar{p}} \{u * [U(p, \sigma_{\mathcal{M}}, \theta_{\mathcal{M}}) - C(\sigma_{\mathcal{M}}, \theta_{\mathcal{M}})] + (1 - u) * [U(p, \sigma_{\mathcal{N}}, \theta_{\mathcal{N}}) - C(\sigma_{\mathcal{N}}, \theta_{\mathcal{N}})]\} f_{\mathcal{P}}(p) dp$$

such that

$$(13) \quad \dot{\theta}_{\mathcal{M}}(p) = -\frac{u * f_{\mathcal{P}}(p)}{\mu f_{\mathcal{N}}(\theta_{\mathcal{M}}(p))}$$

$$(14) \quad \dot{\theta}_{\mathcal{N}}(p) = -\frac{(1 - u) * f_{\mathcal{P}}(p)}{(1 - \mu) f_{\mathcal{N}}(\theta_{\mathcal{N}}(p))}$$

$$(15) \quad \dot{\sigma}_{\mathcal{M}}(p) = \frac{U_p(p, \sigma_{\mathcal{M}}, \theta_{\mathcal{M}})}{C_s(\sigma_{\mathcal{M}}, \theta_{\mathcal{M}}) - U_s(p, \sigma_{\mathcal{M}}, \theta_{\mathcal{M}})}$$

$$(16) \quad \dot{\sigma}_{\mathcal{N}}(p) = \frac{U_p(p, \sigma_{\mathcal{N}}, \theta_{\mathcal{N}})}{C_s(\sigma_{\mathcal{N}}, \theta_{\mathcal{N}}) - U_s(p, \sigma_{\mathcal{N}}, \theta_{\mathcal{N}})}$$

$$(17) \quad \int_{\underline{p}}^{\bar{p}} u(p) f_{\mathcal{P}}(p) dp = \mu$$

$$(18) \quad \sigma_{\mathcal{M}}(\underline{p}) = \sigma_{\mathcal{N}}(\underline{p}) = 520, \theta_{\mathcal{M}}(\underline{p}) = \theta_{\mathcal{N}}(\underline{p}) = 1517$$

The objective of the problem is a rewriting of the average social surplus using the index variable of the control problem, p . Equations 13 - 14 describe how the student-types are allocated to each college, and these equations are derived from the fact that the quota outcome is assortative within each demographic group. Equations 15 - 16 describe how the students' HC choices change as a function of their type, and these conditions are derived from the ODE description of the equilibrium of the quota game (Equation 9) after applying a change of variables. Equation 18 provides boundary conditions for our state variables from Hickman [44]. We impose the boundary condition $\sigma_j(\underline{p}) = \underline{s} = 520$, the lowest SAT score found in our data, regardless of whether or not both groups are assigned seats at the worst school, \underline{p} . We are, in effect, assuming that both groups are assigned at least a small fraction of the seats at every college.

Since the objective function and the equations of motion are linear in u , we know immediately that the solution will have a bang-bang structure. In other words, the social surplus maximizing affirmative action scheme will involve complete segregation - all of the seats in each school will be allocated to one of the two groups. What we find is that the second-best outcome assigns all of the low quality college seats to minority students and reserves the best colleges for non-minority students, a result depicted in Figure 2.

There are two components to the logic underlying the second-best. First, the incentive to compete is driven by the difference in the quality of the prizes. To reduce this incentive, we must make the difference between the best and worst prize available to each group as small as possible, which can be done by breaking the prize space into two intervals.

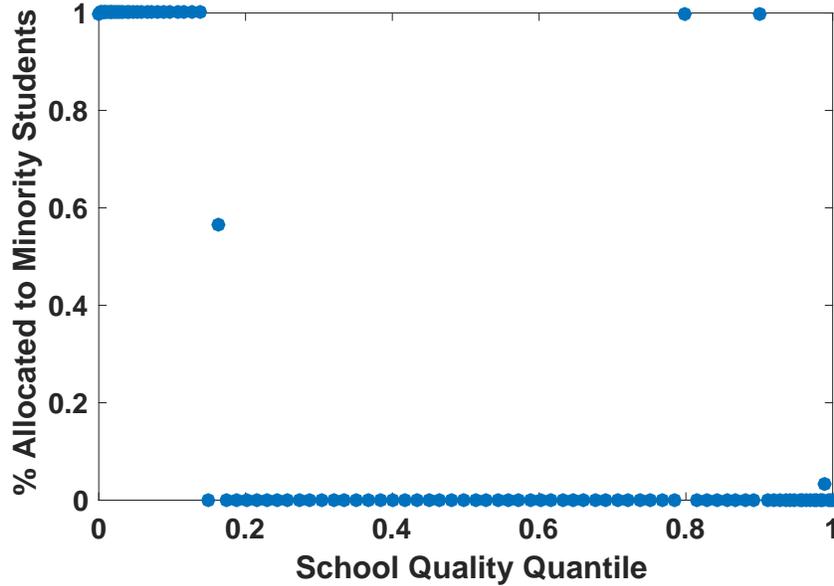


FIGURE 2

Second, maximizing welfare entails assigning the better prizes to the group that will reap larger complementarities from being matched to a high quality school. Since membership in the non-minority group is a signal that human capital accumulation costs are low, the second-best gives the majority of the seats at high quality colleges to non-minority students.

The conclusion we draw from our analysis is that the tension between fairness and welfare is even greater than a comparison between a color-blind and a proportional quota would suggest. In order to reduce the cost of competition, it is necessary to reduce the incentive for the students to compete with each other. One way of doing this, as the second-best reveals, is to allow individuals to compete for only a narrow window of college assignments. In order to choose these narrow windows, any exogenous information available about the students' abilities ought to be brought to bear. In the context of our analysis, the students' minority status is the only useful piece of information. In real life the optimal policy would likely include using other signals of ability such as whether the students' parents are college educated. Again, these systems might be welfare improving in the sense of maximizing the average NPV of lifetime salary, but any system that used these signals would have the effect of perpetuating historical inequities into future generations.

7. NOISY HUMAN CAPITAL MEASURES

In the real world, students do not have complete control over the human capital level observed by colleges. For example, a student's investment in his or her studies might be

highlighted by winning a prestigious academic award, which would boost the student's college placement relative to other students that made the same investment choice. We model the students' imperfect control over the colleges' observations of their HC choices by assuming that for each student, all colleges observe the same noisy human capital (NHC) measure $t = s + \varepsilon$, where s is the level of HC chosen by the student and ε refers to a mean 0 shock to the HC observation. Students are then matched to schools based on the NHC measure t . The important features of the shock is that (1) it is unobserved by the student until after the human capital choice has been made and (2) it is common across colleges. We assume throughout that ε has a uniformly continuous density function f_ε and CDF F_ε and has full support.

The noisy human capital values have two effects. First, and most obviously, it makes the outcomes of any particular action stochastic, which makes the analysis significantly more complicated. The primary difficulty is that we can no longer write down useful versions of the differential equations we used to characterize the equilibrium without noise. Second, the shocks to HC have the effect of placing students with different HC choices at the same school.

When discussing admissions preference systems, we assume that the mark-up function \tilde{T} is applied to the NHC values. We need the following assumption for the mark-up function to be well behaved.

Assumption 11. *There exists $\lambda_1, \lambda_2 \in (0, \infty)$ such that for all t we have*

$$\lambda_2 > \tilde{T}'(t) > \lambda_1$$

The definitions of the assignment mappings P_j^r is similar to those in Sections 3 and 4 with t playing the role of s . Given a vector \mathbf{t}_{-i} of the other players' NHC levels in the finite agent game, we let $P_j^r(\cdot, \mathbf{t}_{-i}) : \mathcal{T} \rightarrow \mathcal{P}_K$, $j \in \{\mathcal{M}, \mathcal{N}\}$ and $r \in \{cb, q, ap\}$, be an assignment mapping that describes the college to which student i is assigned given each possible NHC realization. For example, the color-blind assignment mapping in the finite game is:

$$P_{\mathcal{M}}^{cb}(t_i, \mathbf{t}_{-i}) = P_{\mathcal{N}}^{cb}(t_i, \mathbf{t}_{-i}) = P^{cb}(t_i, \mathbf{t}_{-i}) = \sum_{k=1}^K p(k : K) \mathbb{1}[t_i = t(k : K)].$$

In the limit model, the color-blind assignment mapping is:

$$(19) \quad P_{\mathcal{M}}^{cb}(t) = P_{\mathcal{N}}^{cb}(t) = F_p^{-1} \left(\mu H_{\mathcal{M}}^{cb}(t) + (1 - \mu) H_{\mathcal{N}}^{cb}(t) \right)$$

where H_j^r is the equilibrium cumulative distribution function of NHC values.

The ex post payoff for student i is then:

$$(20) \quad \Pi_j^r(s_i, \mathbf{s}_{-i}; \theta) = E \left[U \left(P_j^r(t_i, \mathbf{t}_{-i}), s_i, \theta_i \right) \mid s_i, \mathbf{s}_{-i} \right] - C(s_i, \theta_i)$$

The expectation in Equation 20 reflects uncertainty over both the types of the other agents and the values of ε drawn for each player. In the limit game, the analogous utility is:

$$(21) \quad \Pi_j^r(s; \theta) = E \left[U \left(P_j^r(t), s, \theta \right) | s \right] - C(s, \theta)$$

The expectation in Equation 21 reflects uncertainty about the agent's own value of ε .

For brevity, we quickly state analogs for our equilibrium existence and approximation results and focus the discussion on the differences between the claims and proof techniques relative to the noise-free benchmark model. First we use the supermodularity of the game to prove the existence of an equilibrium using techniques similar to those employed to prove Theorem 1.

Theorem 5. *In the finite agent college admissions game $\Gamma(K_{\mathcal{M}}, F_{\mathcal{M}}, K_{\mathcal{N}}, F_{\mathcal{N}}, \mathcal{P}_{\mathcal{K}})$ with $r \in \{cb, q, ap\}$, under assumptions 1–8 there exists a monotone pure-strategy equilibrium.*

We can extend the supermodularity techniques used to prove Theorem 5 to prove equilibria exist in the limit model with noise. In contrast, the proof of Theorem 2 was proven using an analysis of the ODEs characterizing the equilibrium of the limit model. We cannot prove that the limit equilibrium is essentially unique since we cannot appeal to analogous ODEs in the model with noise.

Theorem 6. *There exists a monotone, pure strategy Nash equilibrium of our limit model in the color-blind, quota, or admissions preference systems.*

Finally, we obtain the following approximation result

Theorem 7. *Let σ_i^j , $i \in \{\mathcal{M}, \mathcal{N}\}$ and $j \in \{cb, q, ap\}$ denote an equilibrium of the limit game. We can choose K^* such that σ_i^j is a ε -approximate equilibrium of the K -agent game for any $K > K^*$.*

Our result is stronger than Theorem 3 in that we do not require that the quotas have a connected support. Theorem 3 is stronger in that we prove that the equilibrium of the limit game is also a δ -approximate equilibrium, which relied on the uniqueness of the limit game's equilibrium. It is, however, easy to prove that if we consider a sequence $\left\{ \left(\sigma_{\mathcal{M}}^{j,K}, \sigma_{\mathcal{N}}^{j,K} \right) \right\}_{K=1}^{\infty}$ where $\left(\sigma_{\mathcal{M}}^{j,K}, \sigma_{\mathcal{N}}^{j,K} \right)$ is an equilibrium of the K -agent game, then $\left\{ \left(\sigma_{\mathcal{M}}^{j,K}, \sigma_{\mathcal{N}}^{j,K} \right) \right\}_{K=1}^{\infty}$ converges to an equilibrium of the limit game (if it converges at all).

Finally, Theorem 4 on the equivalence of quota and admissions preference schemes extends to a model with noisy observations of human capital. To see this, note that if one simply replaces the use of s in the proof of Theorem 4 with t , the argument applies immediately to the NHC model. We state the theorem here for completeness.

Theorem 8. *$P_j^q(t) : \mathbb{R} \rightarrow \mathcal{P}$, $j \in \{\mathcal{M}, \mathcal{N}\}$, is the result of an equilibrium of some quota system with $Q_{\mathcal{M}}, Q_{\mathcal{N}}$ if and only if there is admissions preference system with \tilde{T} that has the same equilibrium assignment mappings and strategies.*

8. CONCLUSION

The purpose of this paper has been to introduce a new model of college admissions and use it to enrich the debate around the differences between quota and admissions preference systems as well as throw light on the welfare costs of the competition for admission, which anecdotal evidence suggests has ratcheted up in intensity in recent years. Modeling college admissions and affirmative action programs is challenging since one must consider the human capital investment decisions of students, heterogeneity in the underlying quality of the colleges and the ability of the students, and the decisions of universities given the information they are presented. Prior papers in the literature gain tractability by simplifying various components of the problem (e.g., assuming all college are homogenous or student quality is innate). We instead consider a market with a continuum of agents, and the continuum approximation greatly simplifies the analysis and allows us to produce a number of novel results.

Our first application of the model is to study the difference between quota-based and admissions preference-based affirmative action systems, and we find that there is no difference in the equilibrium outcomes produced. It is not particularly surprising that one can achieve the same diversity levels at each institution under each scheme. We believe it is more surprising that the equivalence also holds for the human capital accumulation decisions of the students.

Our equivalence formalizes comments made in the jurisprudence regarding the difference between quotas and affirmative action schemes. The legality of affirmative action turns on what was perceived by Justice Powell as a difference between quotas and narrowly tailored admissions preference systems. Later opinions about the legality of different admissions preference schemes hinged on how closely the respective justice thought the admissions preference scheme mimicked the outcomes of a quota. Our analysis suggests that drawing a sharp line between quotas and admissions preference schemes based on outcomes may be futile.

We also analyze the welfare effects of competition for college admission using a calibration of our model drawn from Hickman [44] that used admissions data from 1995 - 1996 application year. In an incomplete information world, competition is necessary to achieve an efficient, assortative match between students and colleges. Our analysis suggests that competition wipes out over \$91,000 of the NPV of the college salary premium for the average student, which is 13% of the total college premium. Stated differently, the college admissions contest quadruples the average cost of preparing for college in terms of the NPV of future income.

Anecdotal evidence from news reports and books such as the *Battle Hymn of the Tiger Mother* by Amy Chua and *The Overachievers: The Secret Lives of Driven Kids* by Alexandra

Robbins suggest that the pressures being placed on high school students may be increasing with time. Since our study focuses on individuals that graduated from college more than 20 years ago, we believe our estimates are a lower bound on the present costs of college competition. Studying the time trend of the college competition costs would allow us to address whether the costs are increasing over time and the effect of high achieving foreign students on student welfare.

Our final contribution is to analyze a model where the assignment to colleges is based on a noisy measure of human capital. We are at present estimating this model, and hope to use the results to speak to issues such as the relative contribution of human capital, innate ability, and college quality to labor market outcomes.

Three other interesting directions for further research exist. First, if we could incorporate a model of how student assignment endogenously influences college quality, we could discuss with more confidence the general equilibrium implications of massive changes in the assignment of students to schools.

Second, the current model focuses on student behavior, conditional on participation in the college market, but there is another interesting group of individuals to consider as well: those whose decision to attend college may be affected by a given policy. This question could be addressed by formalizing the “supply-side” comprised of potential colleges and firms who may enter the market and supply post-secondary education services or unskilled jobs. Such a model might illustrate how the marginal agent (i.e., the individual indifferent between attending college and entering the workforce) is affected by a given college admission policy. This would help to characterize the full effect of AA.

Finally, the eventual goal for this line of research should be to answer the question of how AA helps or hinders the objective of erasing the effects of institutionalized racism. This will require a dynamic model in which the policy-maker is not only concerned with short-term outcomes for students whose types are fixed, but also with the long-run evolution of the type distributions. Empirical evidence suggests that academic competitiveness is determined by factors such as affluence and parental education. If AA affects performance and outcomes for current minority students, then the next question is what effect it might have on their children’s competitiveness when the next generation enters high school? If a given policy produces the effect of better minority enrollment and higher achievement in the short-run, then one might conjecture that a positive long-run effect will be produced. However, it seems evident that a long-run model is needed in order to give meaningful direction to forward-looking policy-makers. It is our hope that the theory developed here will help in the development of a model that addresses these important questions in the future.

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APPENDIX A. PROOFS

We break our proofs into three sections. Section A.1 contain the proofs of the majority of our results. Section A.2 contains the proof of Theorem 3, which is significantly more involved than our other arguments. Finally, section A.3 contain the proofs for our claims regarding the extension of our model to a setting where human capital is observed with noise.

A.1. Proofs. The remaining results in the paper are produced roughly in the order they appear in the main body.

Theorem 1. *In the college admissions game $\Gamma(K_M, F_M, K_N, F_N, \mathcal{P}_K)$ with $r \in \{cb, q, ap\}$, under assumptions 1–8 there exists a monotone pure-strategy equilibrium. Moreover, any equilibrium of the game must be strictly monotone with almost every type using pure strategies.*

Proof. Consider the following gridding of the strategy space $\mathcal{S}_T = \left\{ \underline{s}, \underline{s} + \frac{(\bar{s}-\underline{s})}{T}, \underline{s} + \frac{2(\bar{s}-\underline{s})}{T}, \dots, \bar{s} \right\}$ where T is a natural number, and we refer to the game with actions restricted to \mathcal{S}_T as the T -gridded game. Theorem 1 of Athey [2, Theorem 3] implies the existence of a monotone PSNE on \mathcal{S}_T for any T . Consider a sequence of such monotone PSNE. Since these strategies are monotone and bounded, Helly's selection theorem implies that a subsequence of $(\sigma_i^T)_{T=1}^\infty$ converges to σ_i^* for all i , and for the duration we will let $(\sigma_i^T)_{T=1}^\infty$ denote the convergent subsequence. From Lemma 4 of Athey [2, Theorem 3], we can focus on equilibria where $(\sigma_i^T)_{T=1}^\infty$ (and as a result σ_i^*) have the form $\sigma_i^T(\bar{\theta}) = \sigma_i^*(\bar{\theta}) = \underline{s}$.

Our first step is to prove an analog to Lemma 3 for the case where the action space has been discretized.

Lemma 1. *σ_i^* must be strictly monotone.*

Proof. First consider the possibility that for agent i there is an interval of the form $[\theta_1, \bar{\theta}]$ where $\sigma_i^*(\theta) = \underline{s}$ for all $\theta \in [\theta_1, \bar{\theta}]$. Since player i chooses \underline{s} with positive probability ρ in the limit game, for any $\delta > 0$ we can choose T sufficiently large that player i chooses an action within $[\underline{s}, \underline{s} + \delta]$ with probability at least ρ in the T -gridded game.

Note that in any equilibrium we must have for agents $j \neq i$ that $\sigma_j^*(\bar{\theta}) = \underline{s}$. If these player-types choose \underline{s} , then they have a positive probability of tying with agent i and receive (at random) one of the worst school assignments available. By deviating to $\underline{s} + \delta$ for an arbitrarily small cost (since δ can be chosen to be arbitrarily small), player j with type

$\bar{\theta}$ can with probability ρ instead receive the second-worst (or better) school assignment, which is a discrete improvement. Therefore it cannot be the case that player j with type $\bar{\theta}$ finds it optimal to choose \bar{s} when T is sufficiently large. From this contradiction we conclude that there cannot exist an interval of the form $[\theta_1, \bar{\theta}]$ where $\sigma_i^*(\theta) = \underline{s}$ for all $\theta \in [\theta_1, \bar{\theta}]$ for any player.

Now we turn to the possibility of violations of strict monotonicity at higher human capital levels. Suppose for some i we have that σ_i^* is not monotone, which means there exists $s \in (\underline{s}, \bar{s})$ and an interval $[\theta_1, \theta_2]$ such that $\sigma_i^*(\theta) = s > \underline{s}$ for $\theta \in [\theta_1, \theta_2]$. Let ρ denote the probability with which player i plays s . From the convergence of $(\sigma_i^T)_{T=1}^\infty$, for any $\delta > 0$ there exists T^* sufficiently large that for all $T > T^*$ and $\theta \in [\theta_1, \theta_2]$ we have $\sigma_i^T(\theta) \in (s - \delta, s + \delta)$.

We now argue that no player $j \neq i$ can find it optimal in equilibrium to play $s \in (s - \delta, s + \delta)$ for sufficiently large T where $\delta > 1/T$. To see this, note that if $\sigma_j^*(\theta) \in (s - \delta, s + \delta)$, then by choosing $\tilde{s} = s + \delta$, player j has a probability ρ of discretely improving his outcome by surpassing player i 's effort level. Since δ (and hence the cost of this deviation) can be chosen to be arbitrarily small and the benefit remains bounded strictly above 0, the existence of such a profitable deviation proves our claim.

Having established that no agent $j \neq i$ chooses s within $s \in (s - \delta, s + \delta)$ with positive probability, we know that there is no competitive channel of incentives active at HC level s . This means that in the agent must be indifferent across all choices of s in $(s - \delta, s + \delta)$. However, since U and C are strictly convex in s , this is impossible. From this contradiction we can conclude that σ_i^* is strictly monotone. \square

Now we use Lemma 1 to argue that the utility in the T -gridded game converges to the utility received in the game with the continuum of actions. Let $\Pi_i(s, \sigma_{-i}, \theta)$ denote the expected utility of agent i with type θ playing action s when the other agents choose according to σ_{-i} .

Lemma 2. Consider $s_T \rightarrow s$ when $T \rightarrow \infty$ where $s_T \in \mathcal{S}_T$. Then $\Pi_i(s_T, \sigma_{-i}^T, \theta) \rightarrow \Pi_i(s, \sigma_{-i}^*, \theta)$.

Proof. First decompose $\Pi_i(s_T, \sigma_{-i}^T, \theta) \rightarrow \Pi_i(s, \sigma_{-i}^*, \theta)$ into two parts

$$(22) \quad \Pi_i(s_T, \sigma_{-i}^T, \theta) - \Pi_i(s, \sigma_{-i}^*, \theta) = \left[\Pi_i(s_T, \sigma_{-i}^*, \theta) - \Pi_i(s, \sigma_{-i}^*, \theta) \right] + \left[\Pi_i(s_T, \sigma_{-i}^T, \theta) - \Pi_i(s_T, \sigma_{-i}^*, \theta) \right]$$

From Lemma 1 we conclude that $\Pi_i(\circ, \sigma_{-i}^*, \theta)$ is continuous since the distribution of college assignments must vary continuously with s since σ_{-i}^* are strictly monotone, $U(p, s, \theta)$ and $C(s, \theta)$ are continuous in s and θ , and F_M and F_N are strictly monotone. But this continuity implies that the first bracketed term of equation 22 approaches 0 as $s_T \rightarrow s$, and from the compactness of \mathcal{S} this convergence is uniform over s .

Now consider the second bracketed term. From the uniform convergence of σ_j^T to σ_j^* , for any $d > 0$ we can choose T sufficiently large that for all agents $j \neq i$ and types θ we

have

$$\sigma_j^T(\theta) - d < \sigma_j^*(\theta) < \sigma_j^T(\theta) + d$$

For any strategy vector σ_{-i} let $\sigma_{-i} + d$ refer to a vector of strategies $\tilde{\sigma}_{-i}$ where for all agents $j \neq i$ we have $\tilde{\sigma}_j(\theta) = \sigma_j(\theta) + d$. Then we can write

$$(23) \quad \left\| \Pi_i(s_T, \sigma_{-i}^T, \theta) - \Pi_i(s_T, \sigma_{-i}^*, \theta) \right\| \leq \Pi_i(s_T, \sigma_{-i}^* - d, \theta) - \Pi_i(s_T, \sigma_{-i}^* + d, \theta)$$

From the strict monotonicity of σ_j^* , we know that the right side of equation 23 vanishes in the limit as $d \rightarrow 0$, which means that the second bracketed term of equation 22 vanishes in the limit as $T \rightarrow \infty$. \square

Now we use lemma 2 to close our argument regarding existence. Since σ^T represents an equilibrium of the T -gridded game, we know that for all players and all types θ and all actions $s \in \mathcal{S}_T$

$$(24) \quad \Pi_i(\sigma_i^T(\theta), \sigma_{-i}^T, \theta) \geq \Pi_i(s, \sigma_{-i}^T, \theta)$$

For any $s \in \mathcal{S}$ we can construct a sequence of $(s_T)_{T=1}^\infty$, $s_T \in \mathcal{S}_T$, such that $s_T \rightarrow s$. Lemma 2 allows us to conclude that $\Pi_i(s_T, \sigma_{-i}^T, \theta) \rightarrow \Pi_i(s, \sigma_{-i}^*, \theta)$. Since $\sigma_i^T(\theta) \rightarrow \sigma_i^*(\theta)$ we also have $\Pi_i(\sigma_i^T(\theta), \sigma_{-i}^T, \theta) \rightarrow \Pi_i(\sigma_i^*(\theta), \sigma_{-i}^*, \theta)$. Together with equation 24 we have

$$\Pi_i(\sigma_i^*(\theta), \sigma_{-i}^*, \theta) \geq \Pi_i(s, \sigma_{-i}^*, \theta)$$

which implies $\sigma_i^*(\theta)$ is a best response to σ_{-i}^* for player i . Therefore σ^* is a pure strategy, strictly monotone Bayesian-Nash equilibrium. \square

Theorem 2. *The equilibrium of any of our limit game affirmative action systems is essentially unique, almost all of the agents take pure actions, and the strategies are group-symmetric.*

Proof. In any equilibrium of any of our contests, $P_i^j(s)$ must be monotone increasing, which implies that the function is almost everywhere (under the Lebesgue measure) continuous and differentiable. From supermodularity, we have that the correspondence $s(\theta)$ defined by

$$\mathbf{s}(\theta) = \arg \max_s U(P_i^j(s), s, \theta) - C(s, \theta)$$

is decreasing in the strong set order. Since the objective function is strictly supermodular, $\mathbf{s}(\theta)$ is single valued for almost all θ (under either F_M or F_N). For an agent of type θ to violate group symmetry in equilibrium, it must be that agents of that type have two optimal actions. Similarly, for an agent of type θ to take a mixed action in equilibrium, he must have at least two optimal actions. Since $\mathbf{s}(\theta)$ is almost everywhere single valued, this implies that almost all agents take a pure action in equilibrium and that any equilibrium is group symmetric.

Consider a quota game and assume that σ_i^q is defined by equation 9 over the intervals where Q_i has support. Note that the boundary condition is uniquely defined for any

quota scheme as follows

$$\begin{aligned}\sigma_i^q(\bar{\theta}) &= \arg \max_s U(\underline{p}_i, s, \bar{\theta}) - C(s, \bar{\theta}) \\ \underline{p}_i &= \inf\{p : Q_i(p) > 0\}\end{aligned}$$

$\sigma_i^q(\bar{\theta})$ must be single valued since the problem is strictly concave. By standard results in differential equations, if $[p, p']$ is an interval where Q_i has support and type θ is assigned to college p with human capital level $\sigma_i^q(\theta) = s$, then the strategy is uniquely defined by equation 9 for all types that are (in equilibrium) assigned a seat at a college in $[p, p']$. The only way there could exist two equilibria σ_i^q and $\tilde{\sigma}_i^q$ is if there is some discontinuity at some θ , which could only occur at a gap in the support of Q_i , such that

$$\lim_{\varepsilon \rightarrow 0^+} \sigma_i^q(\theta + \varepsilon) \neq \lim_{\varepsilon \rightarrow 0^+} \tilde{\sigma}_i^q(\theta + \varepsilon)$$

In other words, the jump over an interval in which Q_i lacks support is not uniquely defined. We prove that the first such jump must be uniquely defined. An (omitted) induction step using essentially the same argument can be used to prove that all of the jumps must be uniquely defined.

Suppose that Q_i lacks support over the interval (p, p') and Q_i has full support over both $[\underline{p}, p]$ and $[p', p' + \delta]$ for some $\delta > 0$. Let θ satisfy $P_i^q(\sigma_i^q(\theta)) = p$ - in other words, θ is where the first jump must occur. In equilibrium it must be the case that θ is indifferent about whether to make this jump, so

$$U(p, s, \theta) - C(s, \theta) = U(p', s', \theta) - C(s', \theta)$$

where $s = \sigma_i^q(\theta)$ and $s' = \lim_{\varepsilon \rightarrow 0^+} \sigma_i^q(\theta + \varepsilon)$. Suppose there was a second equilibrium $\tilde{\sigma}_i^q$ starting at type θ such that $s'' = \lim_{\varepsilon \rightarrow 0^+} \tilde{\sigma}_i^q(\theta + \varepsilon) > s'$. Then it must be the case that

$$U(p, s, \theta) - C(s, \theta) = U(p', s', \theta) - C(s', \theta) = U(p', s'', \theta) - C(s'', \theta)$$

But since U_{ss} is strictly concave and C_{ss} is strictly convex, this cannot be true. Therefore s' is uniquely defined.

Since any two equilibria of a quota scheme σ_i^q and $\tilde{\sigma}_i^q$ must be identical except for the countable points θ where a discontinuity occurs, the measure of $\{\theta : \sigma_i^q(\theta) \neq \tilde{\sigma}_i^q(\theta)\}$ is measure 0, which implies the equilibrium is essentially unique.

Now consider an admissions preference game where σ_i^{qp} is defined by equation 12 and is therefore continuous. Standard results on differential equations imply that σ_i^{qp} is uniquely defined.

In all of the affirmative action systems used in the limit game, the equilibria have been defined by ODEs that enforce the local incentive compatibility conditions, but it remains to prove that global incentive compatibility holds. We provide a proof for the admissions preference case, but analogous arguments hold for the quota game. Suppose $\tilde{\theta} < \theta$ and

let $P_i^{ap}(\tilde{\theta}) = \tilde{p} > p = P_i^{ap}(\theta)$ and $\sigma_i^{ap}(\tilde{\theta}) = \tilde{s} > s = \sigma_i^{ap}(\theta)$. We then have from local incentive compatibility that

$$U_p(p, s, \theta) \left. \frac{dP_i^{ap}(\hat{\theta})}{d\hat{\theta}} \right|_{\hat{\theta}=\theta} + U_s(p, s, \theta) \left. \frac{d\sigma_i^{ap}(\hat{\theta})}{d\hat{\theta}} \right|_{\hat{\theta}=\theta} = C_s(s, \theta) \left. \frac{d\sigma_i^{ap}(\hat{\theta})}{d\hat{\theta}} \right|_{\hat{\theta}=\theta}$$

Since $\tilde{\theta} < \theta$, we have from assumption 5 that $U_p(p, s, \tilde{\theta}) > U_p(p, s, \theta)$, and from assumption 6 that $U_s(p, s, \tilde{\theta}) > U_s(p, s, \theta)$ and $C_s(s, \tilde{\theta}) < C_s(s, \theta)$. The value of the first order condition that results if type $\tilde{\theta}$ deviated from truthfulness upwards by declaring $\hat{\theta} = \theta$ is

$$U_p(p, s, \tilde{\theta}) \left. \frac{dP_i^{ap}(\hat{\theta})}{d\hat{\theta}} \right|_{\hat{\theta}=\theta} + U_s(p, s, \tilde{\theta}) \left. \frac{d\sigma_i^{ap}(\hat{\theta})}{d\hat{\theta}} \right|_{\hat{\theta}=\theta} > C_s(s, \tilde{\theta}) \left. \frac{d\sigma_i^{ap}(\hat{\theta})}{d\hat{\theta}} \right|_{\hat{\theta}=\theta}$$

which, since there is an inequality, implies declaring $\hat{\theta} = \theta$ cannot be optimal if the true type is $\tilde{\theta}$. Similar arguments imply that deviating downward from truthfulness also cannot be optimal.

As a final step we must rule out cases where it might be optimal for the agent to choose a human capital level outside of the range of σ_i^{ap} . Since σ_i^{ap} is continuous, this implies that the deviation satisfies $\tilde{s} > s = \sigma_i^{ap}(\underline{\theta})$. Let $p = P_i^{ap}(\underline{\theta})$. We know from our first order conditions that²⁰

$$U_p(p, s, \theta) \left. \frac{dP_i^{ap}(\hat{\theta})}{d\hat{\theta}} \right|_{\hat{\theta}=\theta} + U_s(p, s, \theta) \left. \frac{d\sigma_i^{ap}(\hat{\theta})}{d\hat{\theta}} \right|_{\hat{\theta}=\theta} = C_s(s, \theta) \left. \frac{d\sigma_i^{ap}(\hat{\theta})}{d\hat{\theta}} \right|_{\hat{\theta}=\theta}$$

Increasing from s to \tilde{s} does not change the school p , and so it can only be optimal if

$$(25) \quad U_s(p, \tilde{s}, \theta) = C_s(\tilde{s}, \theta)$$

Since $U_{ss} < 0$, $C_{ss} > 0$, and $U_s(p, s, \theta) \leq C_s(s, \theta)$, equation 25 cannot hold, which means deviating to \tilde{s} cannot be optimal. \square

Theorem 4. Consider some $P_i(s) : \mathcal{S} \rightarrow \mathcal{P}$, $i \in \mathcal{M}, \mathcal{N}$. $P_i(s) : \mathcal{S} \rightarrow \mathcal{P}$, $i \in \mathcal{M}, \mathcal{N}$ is the result of an equilibrium of some quota system if and only if there is an equilibrium of an admissions preference system that also yields these assignment functions and admits the same equilibrium strategies.

Proof. Suppose $P_i^q : \mathcal{S} \rightarrow \mathcal{P}$, $i \in \mathcal{M}, \mathcal{N}$, is the result of an equilibrium of some quota system and denote the equilibrium strategies $\sigma_i^q : \Theta \rightarrow \mathcal{S}$. Since P_i^q and σ_i^q are strictly monotone, the functions are invertible. Let $P^{ap}(s)$, the assignment function under admissions preferences, be $P^{ap}(s) = P_{\mathcal{N}}^q(s)$. Since the assignment functions are the same for the non-minority students, P^{ap} and $P_{\mathcal{N}}^q$ generate identical decision problems for the non-minorities. Therefore, if $\sigma_{\mathcal{N}}^q$ was an equilibrium for non-minority students under $P_{\mathcal{N}}^q$, then $\sigma_{\mathcal{N}}^{ap}(\theta) = \sigma_{\mathcal{N}}^q(\theta)$ will be an equilibrium for the non-minority students under $P^{ap}(s)$.

²⁰We have written the first order condition with the derivatives defined using limits from the right (i.e., using sequences contained in Θ).

To construct the outcome equivalent score function that generates $P^{ap}(s)$, let

$$\tilde{S}(s) = (P_{\mathcal{N}}^q)^{-1}(P_{\mathcal{M}}^q(s))$$

Note that \tilde{S} must be monotone increasing. A minority student who chooses human capital level s will then be assigned to college

$$P^{ap}(\tilde{S}(s)) = P_{\mathcal{N}}^q(\tilde{S}(s)) = P_{\mathcal{N}}^q((P_{\mathcal{N}}^q)^{-1}(P_{\mathcal{M}}^q(s))) = P_{\mathcal{M}}^q(s)$$

Since the assignment functions are the same for the minority students, P^{ap} and $P_{\mathcal{M}}^q$ generate identical decision problems for the minorities. Therefore, if $\sigma_{\mathcal{M}}^q$ was an equilibrium for minority students under $P_{\mathcal{M}}^q$, then $\sigma_{\mathcal{M}}^{ap}(\theta) = \sigma_{\mathcal{M}}^q(\theta)$ will be an equilibrium for the non-minority students under $P^{ap}(s)$.

Now suppose $P^{ap} : \mathcal{S} \rightarrow \mathcal{P}$ with score function \tilde{S} is the result of an equilibrium of some admissions preference system and denote the equilibrium strategies $\sigma_i^{ap} : \Theta \rightarrow \mathcal{S}$, $i \in \mathcal{M}, \mathcal{N}$. To define the equivalent quota system, we need to define allocations of seats to each group. Let these distributions be denoted $Q_i, i \in \mathcal{M}, \mathcal{N}$, and define them as

$$\begin{aligned} \text{For all } p \text{ let } Q_{\mathcal{M}}(p) &= 1 - F_i \left[\psi_i^{ap} \left(\tilde{S}^{-1} \left((P^{ap})^{-1}(p) \right) \right) \right] \\ \text{For all } p \text{ let } Q_{\mathcal{N}}(p) &= 1 - F_i \left[\psi_i^{ap} \left((P^{ap})^{-1}(p) \right) \right] \end{aligned}$$

Given these definitions, $P_{\mathcal{N}}^q(s) = P^{ap}(s)$ and $P_{\mathcal{M}}^q(s) = P^{ap}(\tilde{S}(s))$. Note that the total measure of non-minority students choosing s and minority students choosing $\tilde{S}^{-1}(s)$ under P^{ap} (in equilibrium is)

$$\begin{aligned} 1 - \mu F_{\mathcal{M}} \left[\psi_{\mathcal{M}}^{ap} \left(\tilde{S}^{-1} \left((P^{ap})^{-1}(p) \right) \right) \right] - (1 - \mu) F_{\mathcal{N}} \left[\psi_{\mathcal{N}}^{ap} \left((P^{ap})^{-1}(p) \right) \right] = \\ \mu Q_{\mathcal{M}}(p) + (1 - \mu) Q_{\mathcal{N}}(p) = F_{\mathcal{P}}(p) \end{aligned}$$

which implies $Q_{\mathcal{M}}$ and $Q_{\mathcal{N}}$ are feasible quotas. As argued above, since the decision problems for the agents are the same, the equilibrium strategies in the original admissions preference scheme and the constructed quota are the same. \square

A.2. Proving Theorem 3. Since the equilibrium strategies are strictly decreasing (Proposition 1), we know immediately that the equilibrium strategy must be almost everywhere differentiable. We now prove that there is a lower bound on the derivative of the equilibrium strategy, which implies that the distribution of human capital in any equilibrium must be nonatomic. Moreover, it implies that if we look at sequences of equilibrium strategies, the resulting limit strategy generates a nonatomic distribution of human capital.

Lemma 3. *There exists $\omega < 0$ such that for any equilibrium strategy, $\sigma(\theta)$, of either a finite game or the limit game, we have $\frac{d}{d\theta}\sigma(\theta) < \omega$ at points where the strategy is differentiable.*

Proof. We prove our lemma for the color-blind game, but the proof extends directly to the quota game if we by treat each group separately. Finally, the proof technique easily extends to the score function game, although the notation becomes cumbersome since one must accommodate both groups of students and account for the variation in \tilde{S} .

Suppose there is no such upper bound on the derivative, which means that for any $\omega < 0$ there exists θ such that $\sigma'(\theta) > \omega$. From the a.e. differentiability of σ , there exists an interval $[\theta_L, \theta_U]$ such that $\sigma'(\theta) > \omega$ for all $\theta \in [\theta_L, \theta_U]$ where $\sigma'(\theta)$ exists. Without loss of generality, we assume $\sigma'(\theta)$ exists at θ_L . Let $s_L = \sigma(\theta_L)$ and $s_U = \sigma(\theta_U)$, and note that $0 < s_L - s_U < \omega(\theta_L - \theta_U)$. Since σ must be decreasing, we have

$$\Pr\{\sigma(\theta) \in [s_U, s_L]\} = F(\theta_U) - F(\theta_L)$$

Rearranging this we find

$$\frac{\Pr\{\sigma(\theta) \in [s_U, s_L]\}}{s_L - s_U} = \frac{F(\theta_U) - F(\theta_L)}{\sigma(\theta_U) - \sigma(\theta_L)} > \frac{-1}{\omega} \frac{F(\theta_U) - F(\theta_L)}{\theta_U - \theta_L}$$

Let $\eta_\theta = \inf_{\theta} f(\theta) > 0$. Taking limits we find

$$\lim_{\theta_U \rightarrow \theta_L} \frac{\Pr\{\sigma(\theta) \in [\sigma(\theta_U), \sigma(\theta_L)]\}}{\sigma(\theta_U) - \sigma(\theta_L)} > \frac{-1}{\omega} \lim_{\theta_U \rightarrow \theta_L} \frac{F(\theta_U) - F(\theta_L)}{\theta_U - \theta_L} = \frac{-1}{\omega} f(\theta_L) > \frac{-1}{\omega} \eta_\theta > 0$$

This means that in intervals where $\sigma'(\theta)$ is close to 0, the ‘‘density’’ of individuals making the associated human capital choices is arbitrarily large. We call such a point of high density a pseudo-atom.

Let $\delta_p = \sup_p f_p(p) < \infty$. Increasing the human capital choice from s_L to s_U yields a minimal benefit of increasing the rank of one’s school in the limit game by

$$-\frac{1}{\omega} \frac{\eta_\theta}{\delta_p} (s_L - s_U)$$

If we let $\eta_U = \min_{s,p,\theta} U_p(p, s, \theta) > 0$, then the utility benefit must be at least

$$-\frac{1}{\omega} \frac{\eta_\theta}{\delta_p} \eta_U (s_L - s_U)$$

Let the maximum marginal cost of human capital that we can observe in any equilibrium be denoted

$$\delta_C = \max_{s \in \mathcal{S}, \theta \in \Theta} C_s(s, \theta) < \infty$$

This means the cost of deviating from s_U to s_L is bounded from above by

$$(s_L - s_U) \delta_C$$

For such a deviation to be suboptimal, we must have

$$(s_L - s_U) \delta_C \geq -\frac{\eta_U}{\omega} \frac{\eta_\theta}{\delta_p} (s_L - s_U)$$

which requires

$$\sigma'(\theta) \leq \omega \leq -\frac{\eta_\theta \eta_U}{\delta_p \delta_C}$$

In the game with K students, the formation of pseudo-atoms is probabilistic. Consider an agent with type θ_U who in equilibrium chooses $s_U = \sigma^K(\theta)$. Suppose such a student considers increasing her human capital choice to s_L . For each student she leap frogs, her school placement improves by at least $(\delta_p)^{-1} \frac{1}{K}$, which generates a utility benefit of at least

$$\frac{\eta_U}{\delta_p} \frac{1}{K}$$

For each student, there is a probability of at least $-\frac{\eta_\theta}{\omega}(s_L - s_U)$ of observing a human capital choice in $[s_U, s_L]$, which yields a lower bound on the expected benefit of the deviation equal to

$$\frac{\eta_U}{\delta_p} \frac{1}{K} E[i]$$

where i is distributed binomially with K draws using a parameter equal to $-\frac{\eta_\theta}{\omega}(s_L - s_U)$. Given the distribution of i , we can write

$$\frac{\eta_U}{\delta_p} \frac{1}{K} E[i] = \frac{\eta_U}{\delta_p} \frac{1}{K} \left[-\frac{\eta_\theta}{\omega} (s_L - s_U) K \right] = -\frac{\eta_U}{\delta_p} \frac{\eta_\theta}{\omega} (s_L - s_U)$$

The remainder of the argument proceeds as above. \square

Before proving our approximation results, we provide a few background results from the theory of the weak convergence of empirical processes. Below we restate the Glivenko-Cantelli theorem for reference.

Theorem 9. Consider a random variable $X : \Omega \rightarrow \mathbb{R}$ with CDF $F(y) = \int_{\Omega} 1\{x \leq y\} * \pi_0(dx)$. For N i.i.d. realizations, $\{X_1, \dots, X_N\}$ denote the N realization empirical CDF as $F_N(y)$. Then we have

$$\sup_{y \in \mathbb{R}^d} \|F_N(y) - F(y)\| \rightarrow 0 \text{ almost surely as } N \rightarrow \infty$$

The topology over the space of measures generated by the sup-norm over the space of CDFs is referred to as the *Kolmogorov topology*. It is straightforward to show that the Kolmogorov topology and the weak-* topology²¹ are identical over any space of nonatomic measures.

With this background in hand, we can now proceed with the proof of our approximation results.

Theorem 3. Consider any admissions preference game or a quota game where $Q_{\mathcal{M}}$ and $Q_{\mathcal{N}}$ admit strictly positive PDFs over a connected support. Let σ_i^j , $i \in \mathcal{M}, \mathcal{N}$ and $j \in \{cb, ap, q\}$ denote an

²¹The Prokhorov-Levy metric that metricizes the weak-* topology and the sup-norm over the space of CDFs are identical when one of the measures is nonatomic.

equilibrium of the limit game. Under assumptions 1 -9 and given $\varepsilon, \delta > 0$, there exists $K^* \in \mathbb{N}$ such that for any $K \geq K^*$ we have that σ_i^j is a ε -approximate equilibrium and a δ -approximate equilibrium of the K -agent game.

Proof. We prove our theorem through a series of lemmas. These lemmas are necessary for the application of the theorems in Bodoh-Creed [9].

Since our proofs rely on results on the convergence of empirical processes to their true distributions, we will need to define the spaces in which these measures live. The true distributions of the student types are $F_{\mathcal{M}}(\theta)$ or $F_{\mathcal{N}}(\theta)$. We have assumed that these distributions have strictly positive densities, which means that their respective PDFs are bounded from below. This means that we can define a compact set Δ^Θ of measures over Θ such that $F_{\mathcal{M}}(\theta), F_{\mathcal{N}}(\theta) \in \Delta^\Theta$ and all of the measures in Δ^Θ have PDFs that are uniformly and strictly bounded above 0. We endow the space Δ^Θ with the Kolmogorov topology.

First we establish some initial properties of the objects we are working with. Lemma 3 establishes that the equilibrium strategies have an upper bound on their derivative, which implies that pseudo-atoms cannot exist. Let Σ^R be the set of strategies that adhere to the bound prescribed by lemma 3, and we endow this space with the L^1 norm. Since these are functions of bounded variation, Σ^R is compact by the Helly Selection Theorem. From Egorov's theorem, the convergence is also "almost" uniform in the sense that it can be metricized by the norm:

$$d_{AU}(\sigma, \tilde{\sigma}) < \delta \text{ if } \|\sigma(\theta) - \tilde{\sigma}(\theta)\| < \delta \text{ for a set of } \Theta_{AU} \text{ of measure } 1 - \delta \text{ w.r.t. } F_j$$

The monotonicity of the members of Σ^R implies that $\Sigma^R - \Theta_{AU}$ can be described as a countable set of closed intervals.²²

Let $\Delta^R(\mathcal{S})$ denote the space of pushforward measures generated by a strategy $\sigma \in \Sigma^R$ and a distribution of student types, $F_i(\theta) \in \Delta^\Theta$. The set $\Delta^R(\mathcal{S})$ is a tight family of measures and is compact (Theorem 15.22 of Aliprantis and Border [1]). We endow the space $\Delta^R(\mathcal{S})$ with the weak-* topology. Since the measures in $\Delta^R(\mathcal{S})$ are all nonatomic, the weak-* topology is equivalent to the Kolmogorov topology generated by the sup-norm applies to the space of CDFs.

Let $\Delta_K(X)$ denote the set of empirical measures generated K draws from the set X . We will let $G_{\mathcal{N}}^{K_{\mathcal{N}}}$ denote the CDF of the empirical measure of human capital choices for the non-minority students when there are $K_{\mathcal{N}}$ such students in the economy, and we use the notation $\Delta_{K_{\mathcal{N}}}(\mathcal{S})$ to refer to the set of such CDFs. $G_{\mathcal{M}}^{K_{\mathcal{M}}}$ denotes the empirical measure of human capital choices for the minority students when there are $K_{\mathcal{M}}$ such students in the economy, and we use $\Delta_{K_{\mathcal{M}}}(\mathcal{S})$ to refer to the set of such CDFs. We endow $\Delta_{K_{\mathcal{N}}}(\mathcal{S})$ and $\Delta_{K_{\mathcal{M}}}(\mathcal{S})$ with the weak-* topology.

²²These intervals may be required to include points where the uniform closeness condition holds, although the measure of Θ_{AU} will still meet the requirements of the almost uniform convergence.

We now prove two useful lemmas about inverse functions that, for some reason, we cannot find in the existing literature.

Lemma 4. *Let $G_j, j \in \{\mathcal{M}, \mathcal{N}\}$ be the CDF of the pushforward measure generated by $\sigma_j \in \Sigma^R$ and the type distribution $F_j \in \Delta^\Theta$. Then G_j is uniformly continuous in σ_j when the space of CDFs is endowed with the sup-norm.*

Proof. Consider σ_j with the associated pushforward measure G_j . Then

$$G_j = F_j \left(\sigma_j^{-1}(s) \right) = F_j \left(\{ \theta : \sigma_j(\theta) \leq s \} \right)$$

Choose any $\epsilon > 0$. Consider an arbitrary $\tilde{\sigma}$ such that $d_{AU}(\tilde{\sigma}_j, \sigma_j) < \delta$, and denote the associated pushforward measure $\tilde{G}_j(s)$. For any $T \in \mathbb{N}$ consider the set $\{0, \frac{1}{T}, \frac{2}{T}, \dots, 1\}$ that grids quantile space. Let Θ_{Cut} include all θ such that $\|\tilde{\sigma}_j(\theta) - \sigma_j(\theta)\| > \delta$, and (as noted above) there exists a Θ_{Cut} that is a countable set of closed intervals. This means that for δ sufficiently small we can choose a set $\Theta_{Grid} = \{\theta_1, \dots, \theta_T\}, \theta_i \in [\underline{\theta}, \bar{\theta}]$, where $\theta_i \in \left[F_j^{-1}\left(\frac{i}{T}\right), F_j^{-1}\left(\frac{i+1}{T}\right) \right]$ and $\theta_i \notin \Theta_{Cut}$.

For each θ_i we have for $\delta > 0$ sufficiently small $\left\| \tilde{\sigma}_j^{-1}(\sigma_j(\theta_i)) - \theta_i \right\| < \epsilon$ for all $\theta_i \in \Theta_{Grid}$.²³ This combined with the continuity and monotonicity of F_j implies that for all $\theta \in \Theta_{Grid}$ we have $\left\| G_j(\sigma_j(\theta)) - \tilde{G}_j(\sigma_j(\theta)) \right\| < \epsilon + \frac{2}{T}$. Since G and \tilde{G} are monotone, for any $\epsilon > 0$ we can choose $\delta > 0$ sufficiently small and T sufficiently large that

$$\sup_{s \in [\underline{s}, \bar{s}]} \left\| G_j(s) - \tilde{G}_j(s) \right\| < \epsilon$$

□

Lemma 5. *Let K be any increasing function where for some $\gamma > 0$ and any $t > t'$ we have $K(t) - K(t') \geq \gamma(t - t')$. Then $K^{-1}(\cdot)$ is uniformly continuous.*

Proof. Consider k, k' where $K(t) = k$ and $K(t') = k'$. Then we have

$$\begin{aligned} \|k - k'\| &> \gamma \|t - t'\| \\ \|t - t'\| &< \frac{1}{\gamma} \|k - k'\| \end{aligned}$$

which implies that $K^{-1}(\cdot)$ is uniformly continuous. □

Our next lemma proves that the limit assignment mapping must be continuous in both s and the distributions of agent actions, $G_j, j \in \{\mathcal{M}, \mathcal{N}\}$. To this end, let $P_j^r(\cdot; G_{\mathcal{N}}, G_{\mathcal{M}})$

²³A quick proof of this claim starts by noting that for any θ

$$\begin{aligned} \sigma_j(\theta - \epsilon) &< \sigma_j(\theta) - \omega\epsilon \\ \sigma_j(\theta + \epsilon) &< \sigma_j(\theta) + \omega\epsilon \end{aligned}$$

For any ϵ choose $\delta < \omega\epsilon$ and choose $\tilde{\sigma}_j$ such that $\left\| \sigma_j(\theta) - \tilde{\sigma}_j(\theta) \right\| < \delta$, which implies $\tilde{\sigma}_j(\theta) \in [\sigma_j(\theta) - \delta, \sigma_j(\theta) + \delta] \subset (\sigma_j(\theta) - \omega\epsilon, \sigma_j(\theta) + \omega\epsilon)$ which implies $\tilde{\sigma}_j^{-1}(s) \in (\theta - \epsilon, \theta + \epsilon)$ as required.

denote the assignment mapping generated if the agent actions are distributed as per $(G_{\mathcal{N}}, G_{\mathcal{M}})$.

Lemma 6. $P_j^r(s; G_{\mathcal{N}}, G_{\mathcal{M}})$, $j \in \{\mathcal{M}, \mathcal{N}\}$ and $r \in \{cb, q, ap\}$, is uniformly continuous in $(s, G_{\mathcal{N}}, G_{\mathcal{M}})$.

Proof. We provide a proof for the admissions preference game since the other systems are special cases of an admissions preference scheme. In the admissions preference game, we have $P_{\mathcal{M}}^{ap}(s) = F_{\mathcal{P}}^{-1} \left((1 - \mu)G_{\mathcal{N}}(\tilde{S}(s)) + \mu G_{\mathcal{M}}(s) \right)$. Let

$$\begin{aligned} q(s) &= (1 - \mu)G_{\mathcal{N}}(\tilde{S}(s)) + \mu G_{\mathcal{M}}(s) \\ \tilde{q}(s') &= (1 - \mu)\tilde{G}_{\mathcal{N}}(\tilde{S}(s')) + \mu\tilde{G}_{\mathcal{M}}(s') \end{aligned}$$

$G_{\mathcal{N}}$ and $G_{\mathcal{M}}$ must be uniformly continuous with respect to s since the slopes of $\sigma_{\mathcal{N}}$ and $\sigma_{\mathcal{M}}$ are strictly bounded away from 0 and \tilde{S} is uniformly continuous from assumption 8. Therefore, for any $\gamma > 0$ we can choose $\delta > 0$ sufficiently small that for any $(s, G_{\mathcal{N}}, G_{\mathcal{M}})$ and $(s'; \tilde{G}_{\mathcal{N}}, \tilde{G}_{\mathcal{M}})$ that satisfy

$$\|G_{\mathcal{N}} - \tilde{G}_{\mathcal{N}}\| + \|G_{\mathcal{M}} - \tilde{G}_{\mathcal{M}}\| + \|s - s'\| < \delta$$

we have

$$\begin{aligned} \|\tilde{q}(s') - q(s)\| &< \left\| q(s) - \left[(1 - \mu)G_{\mathcal{N}}(\tilde{S}(s')) + \mu G_{\mathcal{M}}(s') \right] \right\| + \delta \\ &< \left\| q(s) - \left[(1 - \mu)G_{\mathcal{N}}(\tilde{S}(s)) + \mu G_{\mathcal{M}}(s) \right] \right\| + \delta + \frac{\gamma}{2} \\ &= \delta + \frac{\gamma}{2} < \gamma \end{aligned}$$

$f_{\mathcal{P}}$ has a lower bound, meaning $F_{\mathcal{P}}$ has a lower bound on its slope and from Lemma 5 $F_{\mathcal{P}}^{-1}$ is uniformly continuous. Therefore for any $\varepsilon > 0$ we can choose $\delta > 0$ sufficiently small that for any $(s, G_{\mathcal{N}}, G_{\mathcal{M}})$ and $(s'; \tilde{G}_{\mathcal{N}}, \tilde{G}_{\mathcal{M}})$ that satisfy

$$\|G_{\mathcal{N}} - \tilde{G}_{\mathcal{N}}\| + \|G_{\mathcal{M}} - \tilde{G}_{\mathcal{M}}\| + \|s - s'\| < \delta$$

we have

$$\left\| P_j^r(s; G_{\mathcal{N}}, G_{\mathcal{M}}) - P_j^r(s'; \tilde{G}_{\mathcal{N}}, \tilde{G}_{\mathcal{M}}) \right\| < \varepsilon$$

which establishes our claim. \square

We use the notation $\Pi_j^r(s, \theta; G_{\mathcal{N}}^{K_{\mathcal{N}}}, G_{\mathcal{M}}^{K_{\mathcal{M}}}, K)$ to refer to the expected utility in the K -agent game of an agent of type θ in demographic group $j \in \{\mathcal{M}, \mathcal{N}\}$ that chooses human capital level s given $G_{\mathcal{N}}^{K_{\mathcal{N}}}$ and $G_{\mathcal{M}}^{K_{\mathcal{M}}}$ and admissions system $r \in \{cb, q, ap\}$. Let $\Pi_j^r(s, \theta; G_{\mathcal{N}}^{K_{\mathcal{N}}}, G_{\mathcal{M}}^{K_{\mathcal{M}}})$ refer to the utility received by an agent of type θ that chooses human capital level s given $G_{\mathcal{N}}^{K_{\mathcal{N}}}$ and $G_{\mathcal{M}}^{K_{\mathcal{M}}}$ in the limit game. Finally we use our lemmas to prove that the agent utility is continuous, which is the linchpin of our ε -approximate equilibrium result.

Lemma 7. $\Pi'_j(s, \theta, G_N, G_M)$ is uniformly continuous in $(s, \theta, G_N, G_M) \in \mathcal{S} \times \Theta \times \Delta(\mathcal{S}) \times \Delta(\mathcal{S})$.

Proof. The continuity result follows from Lemma 6 and the continuity of U and C with respect (p, s, θ) . The uniform equicontinuity comes from the compactness of $\mathcal{S} \times \Theta \times \Delta(\mathcal{S}) \times \Delta(\mathcal{S})$. \square

We now establish our two approximation results in separate lemmas.

Lemma 8. Given the previous assumptions, if $(\sigma_{\mathcal{M}}^{ap}, \sigma_{\mathcal{N}}^{ap})$ is an exact equilibrium of the limit game, then for any $\varepsilon > 0$ we can choose K^* such that for any $K > K^*$ we have that $(\sigma_{\mathcal{M}}^{ap}, \sigma_{\mathcal{N}}^{ap})$ is an ε -approximate equilibrium of the K -agent game

Proof. First note that uniform convergence of the utility functions of the finite model to the limit model is straightforward since conditional on the distribution of human capital, distribution of school qualities, and a particular human capital choice, the school assignment is the same in the finite and the continuum model. Combining this with our result on uniform continuity of the limit game (Lemma 7), Theorem 8 of Bodoh-Creed [9] implies that if $(\sigma_{\mathcal{M}}^{ap}, \sigma_{\mathcal{N}}^{ap})$ is an exact equilibrium of the limit game, then for any $\varepsilon > 0$ we can choose K^* such that for any $K > K^*$ $(\sigma_{\mathcal{M}}^{ap}, \sigma_{\mathcal{N}}^{ap})$ is an ε -approximate equilibrium of the modified K -agent game. \square

Our next result deals with sequences of equilibrium strategies. We use the notation $(\sigma_{\mathcal{M}}^{ap}(K), \sigma_{\mathcal{N}}^{ap}(K))$ to denote an exact equilibrium of the limit game.

Lemma 9. Consider any sequence $\{(\sigma_{\mathcal{M}}^{ap}(K), \sigma_{\mathcal{N}}^{ap}(K))\}_{K=2}^{\infty}$ such that $(\sigma_{\mathcal{M}}^{ap}(K), \sigma_{\mathcal{N}}^{ap}(K)) \rightarrow (\sigma_{\mathcal{M}}^{ap}, \sigma_{\mathcal{N}}^{ap})$. Then under the previous assumptions, $(\sigma_{\mathcal{M}}^{ap}, \sigma_{\mathcal{N}}^{ap})$ is an exact equilibrium of the limit game.²⁴

Proof. Let $(G_{\mathcal{N}}^K, G_{\mathcal{M}}^K)$ refer to the pushforward measure generated by $(\sigma_{\mathcal{M}}^{ap}(K), \sigma_{\mathcal{N}}^{ap}(K))$ and the student type distributions. From Lemma 4 we have $(G_{\mathcal{N}}^K, G_{\mathcal{M}}^K) \rightarrow (G_N, G_M)$ in the sup-norm. Let $(\widehat{G}_{\mathcal{N}}^K, \widehat{G}_{\mathcal{M}}^K)$ denote an empirical measure defined by random draws from $(G_{\mathcal{N}}^K, G_{\mathcal{M}}^K)$ in the K -agent game. From the Glivenko-Cantelli theorem, for any $\rho, \delta > 0$ we can choose K sufficiently large that with probability at least $1 - \rho$

$$\left\| G_{\mathcal{N}}^K - \widehat{G}_{\mathcal{N}}^K \right\| + \left\| G_{\mathcal{M}}^K - \widehat{G}_{\mathcal{M}}^K \right\| < \delta$$

Suppose $(\sigma_{\mathcal{M}}^{ap}, \sigma_{\mathcal{N}}^{ap})$ is not an equilibrium of the limit game. For concreteness, let us assume that minority students of some type θ where $\sigma_{\mathcal{M}}^{ap}(\theta) = s^*$ have a profitable deviation. Formally that means there exists s' and $\varepsilon > 0$ such that

$$\Pi'_{\mathcal{M}}(s^*, \theta; G_N, G_M) + \varepsilon < \Pi'_{\mathcal{M}}(s', \theta; G_N, G_M)$$

²⁴One might have thought theorem 6 of Bodoh-Creed [9] would provide this result. Unfortunately, the proof of that theorem required the strategy space to be compact, which is not be the case in our application.

We now translate this into a statement regarding payoffs in the K -agent game. For sufficiently large K we have with probability at least $1 - \rho$

$$(26) \quad \begin{aligned} \Pi_{\mathcal{M}}^r \left(s^*, \theta; \widehat{G}_{\mathcal{N}}^K, \widehat{G}_{\mathcal{M}}^K \right) + \frac{\varepsilon}{2} &< \Pi_{\mathcal{M}}^r \left(s', \theta; \widehat{G}_{\mathcal{N}}^K, \widehat{G}_{\mathcal{M}}^K \right) \\ \Pi_{\mathcal{M}}^r \left(\sigma_{\mathcal{M}}^{ap}(K), \theta; \widehat{G}_{\mathcal{N}}^K, \widehat{G}_{\mathcal{M}}^K \right) + \frac{\varepsilon}{4} &< \Pi_{\mathcal{M}}^r \left(s', \theta; \widehat{G}_{\mathcal{N}}^K, \widehat{G}_{\mathcal{M}}^K \right) \end{aligned}$$

The first line follows from our continuity result (Lemma 7). The second line follows from our continuity result (with respect to action) and the fact that $\sigma_{\mathcal{M}}^{ap}(K) \rightarrow s^*$ as $K \rightarrow \infty$. Equation 26 implies that for ρ sufficiently small s' represents a profitable deviation for an agent of type θ in the K -agent game. Since the utility function is bounded, allowing us to ignore whatever utility is realized in the residual probability $1 - \rho$ event, this means s' is a profitable deviation from $\sigma_{\mathcal{M}}^{ap}(K)$. From this contradiction we conclude that $(\sigma_{\mathcal{M}}^{ap}, \sigma_{\mathcal{N}}^{ap})$ is an exact equilibrium of the limit game \square

Since Lemma 9 holds for all such sequences of strategies, we have from Theorem 17.16 of Aliprantis and Border [1] that the equilibrium correspondence is upper hemicontinuous.

Our claim regarding δ -approximate equilibria could still fail if there were equilibria of the limit game that were not close to any equilibrium of arbitrarily large finite game. In other words, the argument might fail if the equilibrium correspondence were not lower hemicontinuous in K . Since there is a unique equilibrium of the limit game, it must be the case that the sequence $\{\sigma^K : \Theta \rightarrow \Delta(\mathcal{S})\}_{K=1}^{\infty}$ converges in the sup-norm to the unique equilibrium of the limit game. \square

A.3. Noisy Human Capital Proofs. In this section we use the Lévy metric d_L on CDFs, and we note that convergence under the Lévy metric is equivalent to convergence in the weak-* topology. Given $Y, Z \in \Delta(\mathbb{R})$, $d_L(Y, Z) < \varepsilon$ if for all $x \in \mathbb{R}$ we have

$$Y(x - \varepsilon) - \varepsilon < Z(x) < Y(x + \varepsilon) + \varepsilon$$

This definition in hand, we now prove some basic continuity properties of our model.

Lemma 10. $G_j(s; \sigma_j)$, $j \in \{\mathcal{M}, \mathcal{N}\}$ is continuous in σ_j in the weak-* topology.

Proof. Consider monotone decreasing $\sigma_j, \tilde{\sigma}_j \in \Sigma$ where for a measure $1 - \delta$ of θ we have $\|\sigma_j - \tilde{\sigma}_j\| < \delta$. By definition, $G_j(s; \sigma_j) = F_j(\{\theta : \sigma_j(\theta) \leq s\})$. Using this definition

$$(27) \quad \begin{aligned} G_j(s; \tilde{\sigma}_j) &= F_j(\{\theta : \tilde{\sigma}_j(\theta) \leq s\}) \\ &> F_j(\{\theta : \sigma_j(\theta) \leq s - \delta\}) - \delta \\ &= G_j(s - \delta; \sigma_j) - \delta \end{aligned}$$

Similar algebra can be used to show $G_j(s; \tilde{\sigma}_j) < G_j(s + \delta; \sigma_j) + \delta$, which implies $d_L(G_j(s; \sigma_j), G_j(s; \tilde{\sigma}_j)) < \delta$ as required. \square

Now we turn to the continuity of the assignment mappings in the finite game. First consider the color-blind assignment mapping.

Lemma 11. *In the finite agent game, $\Pr \{P^{cb}(t_i, \mathbf{t}_{-i}) = k | s_i, \mathbf{s}_{-i}\}$ is continuous in s_i and \mathbf{s}_{-i} .*

Proof. In the K agent finite game, we can write the distribution of NHC from the other players as

$$H_K^{cb}(t) = \frac{1}{K-1} \sum_{j \neq i} F_\varepsilon(t - s_j)$$

Since f_ε is uniformly continuous, $H_K^{cb}(t)$ is uniformly continuous in t and \mathbf{s}_{-i} . The probability that $P^{cb}(t) = k$ is just the probability that the agent i 's signal is the k^{th} highest out of \mathcal{K} , which can be written

$$\Pr \{P^{cb}(t_i, \mathbf{t}_{-i}) = k | s_i, \mathbf{s}_{-i}\} = \binom{\mathcal{K}}{k} \int_{-\infty}^{+\infty} H_K^{cb}(s_i + x)^{\mathcal{K}-k} (1 - H_K^{cb}(s_i + x))^{k-1} f_\varepsilon(x) dx$$

Uniform continuity of $\Pr \{P^{cb}(t_i, \mathbf{t}_{-i}) = k | s_i, \mathbf{s}_{-i}\}$ follows from the uniform continuity of H_K^{cb} in t and \mathbf{s}_{-i} . \square

The arguments for the quota case are essentially identical to the color-blind case and are omitted. Now we turn to the admissions preference scheme.

Lemma 12. *In the finite agent game, $\Pr \{P_j^{ap}(t_i, \mathbf{t}_{-i}) = k | s_i, \mathbf{s}_{-i}\}$ is continuous in s_i and \mathbf{s}_{-i} as long as \tilde{T} is continuous and invertible*

Proof. As our first step, we compute the distribution of NHC after applying the markup function, which we denote $H_K^{ap}(t)$. We let $i = 1$ for notational clarity and assume that agent 1 is a nonminority student, but it is obvious that an essentially identical argument would apply if agent i were a minority student. Let $\mathbf{s}_{-i} = (s_2, \dots, s_{K_N}, s_{K_N+1}, \dots, s_{K_N+K_M})$. The

$$H_K^{ap}(t) = \frac{1}{K_N - 1} \sum_{j \neq i} F_\varepsilon(t - s_j) + \frac{1}{K_N - 1} \sum_{j=K_N+1}^{K_N+K_M} F_\varepsilon(\tilde{T}^{-1}(t) - s_j)$$

Since f_ε is uniformly continuous and $H_K^{ap}(t)$ is uniformly continuous in t and \mathbf{s}_{-i} . We can then write

$$\Pr \{P_N^{ap}(t_i, \mathbf{t}_{-i}) = k | s_i, \mathbf{s}_{-i}\} = \binom{\mathcal{K}}{k} \int_{-\infty}^{+\infty} H_K^{ap}(t)(s_i + x)^{\mathcal{K}-k} (1 - H_K^{ap}(t)(s_i + x))^{k-1} f_\varepsilon(x) dx$$

Uniform continuity of $\Pr \{P_N^{ap}(t_i, \mathbf{t}_{-i}) = k | s_i, \mathbf{s}_{-i}\}$ follows from the uniform continuity of H_K^{ap} in t and \mathbf{s}_{-i} . \square

Recall that $\Pi_j^i(s_i, \mathbf{s}_{-i}; \theta)$ denotes the utility of an agent of type θ in the finite game that chooses s_i while the other agents choose \mathbf{s}_{-i} . From Lemmas 11 and 12 we immediately have the following.

Corollary 10. $\Pi_j^r(s_i, \mathbf{s}_{-i}; \theta)$ is continuous in (s_i, \mathbf{s}_{-i}) for $j \in \{\mathcal{M}, \mathcal{N}\}$ and $r \in \{cb, q, ap\}$.

We now prove the analogous result for the limit model.

Lemma 13. $\Pi_j^r(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}; \theta)$ is continuous in $(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ for $j \in \{\mathcal{M}, \mathcal{N}\}$ and $r \in \{cb, q, ap\}$.

Proof. We provide a proof for the admissions preference case, which implies the result for the color-blind and quota systems as are special cases of the admissions preference model. Recall that

$$\Pi_j^r(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}; \theta) = E_\varepsilon \left[U(P_j^{ap}(s + \varepsilon), s, \theta) | \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}} \right] - C(s, \theta)$$

We can write the distribution of marked-up NHC values as

$$H_j^{ap}(t; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}) = (1 - \mu) \int_{\underline{s}}^{\bar{s}} F_\varepsilon(t - s) dG_{\mathcal{N}}(s; \sigma_{\mathcal{N}}) + \mu \int_{\underline{s}}^{\bar{s}} F_\varepsilon(\tilde{T}^{-1}(t) - s) dG_{\mathcal{M}}(s; \sigma_{\mathcal{M}})$$

and since ε is nonatomic, it must be that $H_j(t; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ is continuous in t and strictly increasing. Since G_j is continuous in σ_j under the weak-* topology (Lemma 10) and F_ε is continuous, we know that $H_j(t; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ is also continuous in $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$. Similar argument imply that the PDF of h_j^{ap} is also continuous in t and $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$.

Our goal will be to show that $P_j^{ap}(s + \varepsilon)$ is continuous in s and $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ under the weak-* topology. Since U is continuous in p , this immediately yields that $\Pi_j^{ap}(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}; \theta)$ is continuous in $(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$. We focus on the non-minority students for notational ease, but it is obvious that almost identical arguments hold for the minority students.

Noting that $(H^{ap}(\circ; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}))^{-1}(F_{\mathcal{P}}(p))$ is the NHC level needed to be admitted to school p , we can write the probability of being assigned to school p given $(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ as

$$(28) \quad \Pr \{P_{\mathcal{N}}^{ap}(s + \varepsilon) = p | \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}\} = \frac{f_\varepsilon((H^{ap})^{-1}(F_{\mathcal{P}}(p)) - s)}{h_j^{ap}((H^{ap})^{-1}(F_{\mathcal{P}}(p)))} f_{\mathcal{P}}(p)$$

where we have suppressed the dependence of $(H^{ap})^{-1}$ and h^{ap} on $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$. Equation 28 implies that $\Pr \{P_{\mathcal{N}}^{ap}(s + \varepsilon) = \circ | \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}\}$ will be continuous as long as $h_j^{ap}((H^{ap})^{-1}(\circ))$ is continuous. First consider the density of $h_j^{ap}(\circ; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$

$$h_j^{ap}(t; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}) = (1 - \mu) \int_{\underline{s}}^{\bar{s}} f_\varepsilon(t - s) dG_{\mathcal{N}}(s; \sigma_{\mathcal{N}}) + \mu \int_{\underline{s}}^{\bar{s}} f_\varepsilon(\tilde{T}^{-1}(t) - s) dG_{\mathcal{M}}(s; \sigma_{\mathcal{M}})$$

As $t \rightarrow \pm\infty$, h_j^{ap} approaches 0, which implies $(H_j^{cb})^{-1}$ and $\Pr \{P_{\mathcal{N}}^{ap}(s + \varepsilon) = p | \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}\}$ become discontinuous. However, for sets where h_j^{ap} is bounded above 0, $(H_j^{cb})^{-1}$ and $\Pr \{P_{\mathcal{N}}^{ap}(s + \varepsilon) = p | \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}\}$ are continuous. Our proof strategy is to prove continuity for a central interval of p , and then argue that the outlier school qualities are of such small mass that continuity of $P_{\mathcal{N}}^{ap}(s + \varepsilon)$ under the weak-* topology holds.

To begin, let $(\underline{\sigma}_{\mathcal{M}}, \underline{\sigma}_{\mathcal{N}})$ be the strategy pair where all types chooses \underline{s} , and let $(\bar{\sigma}_{\mathcal{M}}, \bar{\sigma}_{\mathcal{N}})$ be the strategy pair where all types chooses \bar{s} . In turn let $\underline{H}(\circ) = H^{ap}(\circ; \underline{\sigma}_{\mathcal{M}}, \underline{\sigma}_{\mathcal{N}})$ and

$\bar{H}(\circ) = H^{ap}(\circ; \bar{\sigma}_{\mathcal{M}}, \bar{\sigma}_{\mathcal{N}})$. For a given γ , we now define p_1 and p_2 where there is no more than an $\frac{\gamma}{2}$ probability of being assigned a school outside of $[p_1, p_2]$ for any choice of s or $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$. To this end

$$\begin{aligned} \Pr \{P_{\mathcal{N}}^{ap}(s + \varepsilon) = p_1 | \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}\} &= F_{\varepsilon} \left((H^{ap}(\circ; \underline{\sigma}_{\mathcal{M}}, \underline{\sigma}_{\mathcal{N}}))^{-1} (F_{\mathcal{P}}(p_1)) - s \right) \\ &\leq F_{\varepsilon} \left(\underline{H}^{-1} (F_{\mathcal{P}}(p_1)) - \underline{s} \right) = \frac{\gamma}{2} \end{aligned}$$

Solving for p_1 we find

$$p_1 = F_{\mathcal{P}}^{-1} \left[\underline{H} \left(F_{\varepsilon}^{-1} \left(\frac{\gamma}{2} \right) + \underline{s} \right) \right]$$

Using symmetric algebra, we find

$$p_2 = F_{\mathcal{P}}^{-1} \left[\bar{H} \left(F_{\varepsilon}^{-1} \left(1 - \frac{\gamma}{2} \right) + \bar{s} \right) \right]$$

If we can prove continuity of $\Pr \{P_{\mathcal{N}}^{ap}(s + \varepsilon) = p_1 | \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}\}$ over $[p_1, p_2]$ for any $\gamma > 0$, then we have continuity of $P_{\mathcal{N}}^{ap}(s + \varepsilon)$ in the weak-* topology as we can “ignore” the arbitrarily low probability event that $p \notin [p_1, p_2]$.

Since ε has full support, there exists $\underline{h} > 0$ such that $h_j^{ap}(H^{ap})^{-1}(F_{\mathcal{P}}(p)) \geq \underline{h}$ for all $p \in [p_1, p_2]$. This in turn implies that $(H^{ap})^{-1}$ is continuous over $[F_{\mathcal{P}}(p_1), F_{\mathcal{P}}(p_2)]$ and also continuous in $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$. Combined with the continuity of f_{ε} and $f_{\mathcal{P}}$, we know that $\Pr \{P_{\mathcal{N}}^{ap}(s + \varepsilon) = p | \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}\}$ is continuous in p for $p \in [p_1, p_2]$. This implies that $P_{\mathcal{N}}^{ap}(s + \varepsilon)$ is continuous in the weak-* topology. As mentioned at the beginning, we then have that $\Pi_j^{ap}(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}; \theta)$ is continuous in $(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$. \square

We now prove the supermodularity condition required to apply the equilibrium existence theorems of Athey [2].

Lemma 14. $\Pi_j^r(s_i, \mathbf{s}_{-i}; \theta)$ and $\Pi_j^r(s_i, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}; \theta)$ are strictly supermodular in $(s_i, -\theta)$.

Proof. To show supermodularity in the finite game, we must prove that $\frac{\partial \Pi_j^r(s_i, \mathbf{s}_{-i}; \theta)}{\partial \theta}$ is decreasing in s_i . There are two effects to consider. First consider the direct effect of a change in s_i . Assumption 6 implies that $E \left[U_{s\theta}(P_j^r(s_i + \varepsilon, \mathbf{t}_{-i}), s, \theta) \right] - C_{s\theta}(s, \theta) < 0$, so the direct effect has the desired sign. The second, indirect effect is the influence of s_i on P_j^r . Note that increases in s increases the distribution of school assignments in the sense of first order stochastic dominance. Assumption 5 implies that the changes in the distribution of p as s increases also decreases $\frac{\partial \Pi_j^r(s_i, \mathbf{s}_{-i}; \theta)}{\partial \theta}$. Therefore $\Pi_j^r(s_i, \mathbf{s}_{-i}; \theta)$ is supermodular in $(s, -\theta)$. Essentially identical arguments suffice to prove $\Pi_j^r(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}; \theta)$ is supermodular in $(s, -\theta)$ and are omitted. \square

We now prove our equilibrium existence result for the finite game.

Theorem 1. In the college admissions game $\Gamma(K_{\mathcal{M}}, F_{\mathcal{M}}, K_{\mathcal{N}}, F_{\mathcal{N}}, \mathcal{P}_{\mathcal{K}})$ with $r \in \{cb, q, ap\}$, under assumptions 1–8 there exists a monotone pure-strategy equilibrium.

Proof. Lemmas 14 and 10 allow us to use Corollary 2.1 of Athey [2]. \square

We cannot immediately reply the results of Athey to prove an equilibrium exists, but we can come very close.

Theorem 2. *There exists a pure strategy Nash equilibrium of our limit model in the color-blind or admissions preference systems. There exists a pure strategy Nash equilibrium of our limit model in the quota system if Q_j admits a connected support.*

Proof. Define the best response correspondence as

$$s^{BR}(\theta; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}) = \arg \max_s \Pi_j^i(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}; \theta)$$

Lemma 14 combined with Lemma 1 of Athey [2] implies that $s^{BR}(\circ; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ is monotonically ordered in the strong set order. Lemma 2 of Athey [2] implies $s^{BR}(\theta; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ is convex. Finally, because $\Pi_j^i(s, \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}}; \theta)$ is continuous in s and $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ (Lemma 13), we have from the Theorem of the Maximum that $s^{BR}(\theta; \sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$ is upper hemicontinuous in $(\sigma_{\mathcal{M}}, \sigma_{\mathcal{N}})$. It is straightforward to adapt Lemma 3 and Theorems 1 and 2 of Athey [2], which at their core are results about the existence of fixed points and the convergence of sequences of functions, to prove the existence of an equilibrium. \square

We now turn to our approximation result. Given the continuity results we have established, the approximation results follow from theorems in Bodoh-Creed [8].

Theorem 3. *Let σ_i^j , $i \in \mathcal{M}, \mathcal{N}$ and $j \in \{cb, q, ap\}$ denote an equilibrium of the limit game. We can choose K^* such that σ_i^j is a ε -approximate equilibrium of the K -agent game for any $K > K^*$ in the color-blind and admissions preference systems. If Q_j has a connected support, then we can choose K^* such that σ_i^j is a ε -approximate equilibrium of the K -agent game for any $K > K^*$ in the color-blind and admissions preference systems.*

Proof. We can strengthen all of our continuity claims to uniform continuity due to the compactness of the spaces over which U and C are defined. Theorem 7 of Bodoh-Creed [8] then implies σ_i^j is a ε -approximate equilibrium of the K -agent game for any K sufficiently large. \square

APPENDIX B. ONLINE APPENDIX: IDENTIFYING DISCONTINUITIES IN THE EQUILIBRIUM

In this appendix we briefly describe how to identify discontinuities in the equilibrium of the limit game. This section will be of practical interest primarily to practitioners who wish to use equations 9 and 12 to compute equilibria numerically.

First let us consider quota schemes, where jumps are caused by gaps in the support of Q_j . The size of the jump must make the types on the edge of the gap indifferent about making the jump. Formally written, suppose (p_L, p_U) is an interval such that $Q_j((p_L, p_U)) = 0$ and for all $\varepsilon > 0$ we have $Q_j([p_L - \varepsilon, p_U]) > 0$ and $Q_j([p_L, p_U + \varepsilon]) > 0$.

Let θ be such that $P(\sigma_j^q(\theta)) = p_L$. Then it must be that for $s = \lim_{\varepsilon \rightarrow 0^+} \sigma_j^q(\theta + \varepsilon)$ (i.e., the human capital choice on the other side of the jump) we have

$$U(p_L, \sigma_j^q(\theta), \theta) - C(\sigma_j^q(\theta), \theta) = U(p_U, s, \theta) - C(s, \theta)$$

which identifies s .

Now we discuss how to identify gaps in an admissions preference scheme, which are caused by kinks or discontinuities in \tilde{S} . When these issues arise, the marginal incentives for both groups will change. We handle each issue in turn.

First consider a kink in \tilde{S} at s such that $\frac{d}{ds}\tilde{S}$ jumps at s . Without loss of generality, assume that the strategies are lower semicontinuous²⁵ and let $\theta_{\mathcal{N}} = \psi_{\mathcal{N}}^{ap}(s)$ and $\theta_{\mathcal{M}} = \psi_{\mathcal{M}}^{ap}(\tilde{S}^{-1}(s))$, and consider the first order conditions that would have to hold at s if the strategies are continuous

$$\text{For } i = \mathcal{N}, U_p(P^{ap}(s'), s', \theta_{\mathcal{N}}) \left. \frac{dP^{ap}(s)}{ds} \right|_{s=\tilde{S}(s')} + U_s(P^{ap}(s'), s', \theta) = C_s(s', \theta)$$

$$\text{For } i = \mathcal{M}, U_p(P^{ap}(\tilde{S}(s')), s', \theta) \left. \frac{dP^{ap}(s)}{ds} \right|_{s=\tilde{S}(s')} \left. \frac{d\tilde{S}(s)}{ds} \right|_{s=s'} + U_s(P^{ap}(\tilde{S}(s')), s, \theta) = C_s(s', \theta)$$

For both group's strategies to be continuous, we would need the first order conditions across the discontinuity in $\frac{d}{ds}\tilde{S}$ to be continuous. In other words, we would require

$$\frac{dP^{ap}(s)}{ds} = \frac{dP^{ap}(\tilde{S}(s))}{ds} \frac{d\tilde{S}(s)}{ds}$$

which is clearly impossible at the discontinuity in $\frac{d\tilde{S}(s)}{ds}$.

To resolve this problem, one of the groups must jump. We will construct an equilibrium where the minority students jump, but the construction and the test for the validity of the construction is symmetric in the case where the non-minority students jump. If the minority student strategy exhibits a jump, then it must be the case that the first order condition for the non-minority students is smooth across the discontinuity, so $\frac{dP^{ap}(s)}{ds}$ must be continuous. Although convoluted, we write the equation for $\frac{dP^{ap}(s)}{ds}$ below for clarity:

$$\frac{dP^{ap}(s)}{ds} = -\frac{\Phi}{f_P(1-\Phi)} \text{ where } \Phi = \frac{(1-\mu)f_{\mathcal{N}}(\psi_{\mathcal{N}}^{ap}(s))}{(\sigma_{\mathcal{N}}^{ap})'(s)} + \frac{\mu f_{\mathcal{M}}(\psi_{\mathcal{M}}^{ap}(\tilde{S}^{-1}(s)))}{(\sigma_{\mathcal{M}}^{ap})'(s)\tilde{S}'(s)}$$

and we let $(\sigma_i^{ap})'$ be infinity if group i has jumped across that level of human capital. In other words, if the minority students jump, it must be that $(\sigma_{\mathcal{N}}^{ap})'(s)$ drops discontinuously to keep $\frac{dP^{ap}(s)}{ds}$ constant at s . For the duration of the minority student jump, we can use equation 12 to describe the non-minority student strategy. This construction

²⁵Since the edges of these jumps are described by an indifference condition, we could just as easily construct an upper semicontinuous equilibrium.

is successful if in the gap we have for all s within discontinuity in the minority student strategy

$$U_p(P^{ap}(\tilde{S}(s)), s, \theta) \frac{dP^{ap}(s)}{ds} \frac{d\tilde{S}(s)}{ds} + U_s(P^{ap}(\tilde{S}(s)), s, \theta) \geq C_s(s, \theta)$$

If the inequality is reversed, then it must be the case that non-minority student jump and minority students do not. Finally, we need to define the size of the jump in the minority student strategy. Suppose the minority strategy is lower semicontinuous and we have $\sigma_{\mathcal{M}}^{ap}(\theta) = s$ (i.e., θ is the type of minority student that jumps). To define the jump we need to compute s' such that

$$U(P^{ap}(\tilde{S}(s)), s, \theta) - C(s, \theta) = U(P^{ap}(\tilde{S}(s')), s', \theta) - C(s', \theta)$$

and let the minority strategy jump to s' at θ . Again, it will often be the case that the first order conditions for the two groups will not align and

$$\frac{dP^{ap}(s')}{ds} \neq \frac{dP^{ap}(s')}{ds} \frac{d\tilde{S}(s')}{ds}$$

If this occurs, it is treated as noted above. It is easy to construct examples where the groups repeatedly jump and never compete at the same college. For example, if $\tilde{S}(s) = s + \Delta$, $\Delta > 0$, the equilibrium has this structure.

Second, assume that there is a discontinuity in \tilde{S} at human capital level s . Since we have assumed \tilde{S} is increasing, \tilde{S} must jump upwards. Let $\sigma_j^q(\theta) = s$ and assume σ_j^q is lower semicontinuous at θ .²⁶ In this case, there must be a jump in the equilibrium strategy of the minority students that is defined by

$$U(P^{ap}(\tilde{S}(s)), s, \theta) - C(s, \theta) = U(P^{ap}(\tilde{S}(s')), s', \theta) - C(s', \theta)$$

and we let the value of the minority student strategy jump to s' at θ . Again, if the first order conditions cannot both line up, then we will have to allow one of the groups' strategies to jump again, which requires the construction techniques outlined above.

APPENDIX C. DATA AND ESTIMATION

This section is adapted from Hickman [44]. The goal of this appendix is to describe the data and estimation techniques underlying the results used to calibrate the model in Section 6. While this section is meant to be independent from Hickman [44], readers interested in more details or a formal identification argument are referred to the original source for this material.

²⁶The construction would be essentially the same if we chose to let σ_j^q be upper semicontinuous at θ .

TABLE 1. Racial Representation Within Academic Quality Quintiles

Tier	Black	Hispanic	American Indian Alaskan Native	White	Asian Pacific Islander	\mathcal{M}	\mathcal{N}
	11.19%	5.70%	0.76%	71.97%	5.71%	17.65%	82.35%
I	5.45%	5.45%	0.43%	73.69%	10.17%	11.33%	88.67%
II	5.54%	4.63%	0.60%	78.06%	6.64%	10.77%	89.23%
III	10.97%	4.89%	0.76%	74.59%	4.27%	16.62%	83.38%
IV	13.53%	6.11%	0.93%	70.57%	4.53%	20.57%	79.43%
V	20.73%	7.33%	1.11%	63.70%	2.43%	29.17%	70.83%

C.1. US College Admissions Market: 1996. We use US college data for the academic year 1995-1996 because unique data are available (the Baccalaureate and Beyond database) which allow for a link to salary premiums from college attendance.

C.1.1. Colleges. For a sample $L = 1, 2, \dots, L$ of American four-year undergraduate colleges, we have a vector \mathbf{X}_l of institutional characteristics. The first is a quality measure derived from data and methodology by US News & World Report (henceforth, USNWR) for their annual America's Best Colleges rankings. We interpret this as college quality index p_l that ranks the prizes in the admissions contest. We argue that interpreting this index as a meaningful reflection of students' perceived value rankings is sensible for two reasons. First, USNWR solves market information frictions by providing a wealth of data on many schools, along with advice on how to interpret and summarize them. Indeed, the market response to this service has been large enough that rankings are now the primary focus of USNWR's business model and its sole remaining print publication. Second, the validity of USNWR rankings is undoubtedly reinforced in students minds by the enthusiasm with which so many schools advertise their status in America's Best Colleges. A typical undergraduate admissions web page will contain at least some reference to USNWR.

The other data representing colleges are enrollment of first-time freshmen by race provided by the National Center for Education Statistics (NCES) through their Integrated Postsecondary Education Data System (IPEDS) tool. For each school we have a tally of all first-time freshmen (including full-time and part-time) for the following seven racial classifications: White, Black, Hispanic, Asian or Pacific Islander, American Indian or Alaskan Native, non-resident alien, and race unknown. The data representing schools are $\{p_u, M_u, N_u\}_{u=1}^U$, where for the u^{th} school p_u is the USNWR quality index, M_u is the number of seats awarded to minorities—comprising Blacks, Hispanics, and Native Americans—and N_u is the number of seats occupied by non-minorities. These data characterize prizes and market allocations denoted $\mathcal{P}_{\mathcal{K}} = \{p_k\}_{k=1}^K = \{p_{li=1}^{M_l+N_l}\}_{l=1}^L$, $\mathcal{P}_{\mathcal{M}} = \{p_m\}_{m=1}^M = \{p_{li}^{M_l}\}_{i=1, l=1}^{M_l, L}$, and $\mathcal{P}_{\mathcal{N}} = \{p_n\}_{n=1}^N = \{p_{li}^{N_l}\}_{i=1, l=1}^{N_l, L}$, respectively.

In Table 1 schools are sorted in descending order of p and separated into five tiers, with each containing one fifth of the seats in the market. Table entries contain the mass of each race group within each tier. “Minority” race classes are all under-represented in the top two tiers and over-represented in the bottom two. Students fall into \mathcal{M} if they are members of an under-represented racial groups and, as a result, benefit from the status quo affirmative action policy.

Now we turn to justifying our assumption of an atomless distribution of college qualities. The largest college in 1996 (Michigan State) filled 6,989 new freshman seats for a total market share of only 0.66%, and the next ten largest schools (in descending order of size: Purdue, UT-Austin, Texas A&M, Ohio State, U of Illinois at Urbana-Champaign, U of Wisconsin at Madison, U of Michigan at Ann Arbor, Indiana U, Virginia Tech, and Rutgers) combined for only 5.4% of total market supply. The mean, median, and standard deviation seat count within a given school are 804.09, 451, and 934.78, respectively, which translate into market shares of 0.000761, 0.000427, and 0.000885, respectively.

Three other school-level variables will be used to estimate the match utility function: median SAT score (or SAT equivalent of median ACT score) for new freshmen, denoted $S_{0.5,l}$; 6-year graduation rates for the 1996 fall adjusted cohort, denoted ρ_l (both provided by IPEDS); and an estimate of average 10-year annual salary for students who graduated during the 1993-1994 academic year, denoted u_l . The salary measure was derived from the Baccalaureate and Beyond Survey (B&B), which randomly samples colleges and then randomly samples graduates within a given college. The survey includes annual salaries for graduates after 10 years in the workforce. Within each school we average over this post-graduation salary figure for employed graduates not seeking postgraduate education to get an estimate of the expected mid-career salary for students at each school. Finally, we treat the average annual salary for high-school completers in 2002, denoted u_0 , from the Bureau of Labor Statistics and treat this as an outside option to college. Descriptive statistics are reported for institutional data in Table 2.²⁷

C.1.2. *Investment Data.* We have individual-level data on composite SAT scores, race, and other characteristics for a random sample of 76,757 students graduating high-school in 1996 (after eliminating individuals over age 25 to focus on first-time freshmen). The sample of SATs is denoted $S_{\mathcal{K},T} = \{s_t, d_t\}_{t=1}^T$, where d_t is the demographic of the t^{th} test taker and T is the sample size. In order to convert ordinal quality rankings into cardinal utilities, we project school quality and SAT score onto graduation rates and salary premiums. We use the 6-year graduation rate of the 1996 fall cohort, measured in AY2002-03. For the salary premium from graduating from college, we use the mid-career salary averages from the B&B data for the cohort of students graduating in AY1993-94.

²⁷As per IES data security measures, the numbers of observations for B&B variables are rounded to the nearest 10. Min and max are suppressed to avoid compromising confidential data. For within-school 10-year average salaries, the 5th and 95th percentiles, rounded to the nearest \$1,000, are reported instead.

TABLE 2. Descriptive Statistics for Match Partner and Utility Projection Variables

Variable	Obs	Mean	Std. Dev.	Min.	Max.
1996 Graduation Rate (IPEDS)	1281	0.524	0.180	0.033	1
1996 Adjusted Cohort Size (IPEDS)	1281	755.75	912.75	5	6547
Median SAT Score (IPEDS)	1152	999.50	121.91	567	1415
College Quality Index (IPEDS)	1314	0.5129	0.189	0.087	0.973
Variable	Obs	Mean	Std. Dev.	5 th Percentile	95 th Percentile
School Avg. 10-yr Ann. Salary ((B&B, 2002 USD))	540	\$54,226	\$14,847	\$33,000	\$81,000
W/in-School Sample Size ((B&B))	540	12.29	10.79	3	32
Avg. Salary for HS Completers (BLS, 2002 USD)		\$26,133			

The assumptions underlying the utility projection are thus twofold: first, that the 1996 cohort correctly anticipated the effect of school quality and HC on its own graduation prospects; and second, that they correctly anticipated mid-career income premium while they were themselves investing, and that this income premium was their motivation to compete for high-quality college seats.

C.2. ESTIMATION. The structural objects to identify are the type distributions, $F_j(\theta)$; the cost function, $C(s; \theta)$; the match utility function, $U(p, s)$; and the markup, $\tilde{S}(s)$. The set of observables is the prize distribution $F_P(p)$, ex-post match distributions, $F_{P,j}(p)$, the minority mass μ , college-specific covariates $\mathbf{X} = \{\mathbf{X}\}_{l=1}^L = \{p_l, M_l, N_l, S_{0.5,l}, \rho_l, u_l\}_{l=1}^L$, outside utility u_0 , and investment distributions $G_j(s), j \in \{\mathcal{M}, \mathcal{N}\}$. For notational ease, we denote the collective observables by $O = \{F_P, F_{P_M}, F_N, \mu, \mathbf{X}, u_0, G_M, G_N\}$.

C.2.1. Investment Lower Bound. We begin with a preliminary technical concern: the interpretation of minimal investment level \underline{s} . A cursory look at the data suggests a positive SAT lower bound. Another complication is that the SAT is an aptitude test (i.e., it is designed to measure ability), as opposed to the ACT, an achievement test (i.e., it is designed to measure acquired knowledge). Both are used in college admissions. In order to resolve this we turn to the ACT, which near the lower bound measures something closer to investment.

In order to identify the cost-curvature parameter, ν , we assume that the student who obtains the lowest level of HC, \underline{s} , is indifferent between attending and no attending college. In other words:

$$(29) \quad U_p(p, \underline{s}) = C_s(\underline{s}; \bar{\theta}) = \bar{\theta}$$

It is theoretically possible for a student to score zero on the ACT, but such a feat is difficult unless one knows enough to achieve a perfect score: with probability near one, a student will get a positive ACT score by random responding, due to the multiple-choice format of the test. We interpret \underline{s} as a student who randomly responding to all ACT test questions, and we simulated such behavior on an actual ACT exam 100,000 times in order to compute the distribution of resulting scores. The resulting mean, median, and modal scores are 12.12, 12, and 12, respectively (see appendix for further details). The equivalent SAT score range (using concordance tables provided by the test designers) is between 520 and 590, having quantile ranks of 0.0043 and 0.0134, respectively. Data from the supply side of the market lend further support to this as an appropriate range for the minimal investment level: the lowest within-school median SAT score for all colleges in the sample is 567. We set $\underline{s} = 520$, but the estimates were not particularly sensitive to choices of $\underline{s} \in [520, 590]$.

C.2.2. Match Utilities. We use some parametric forms to estimate match utility projection $U(p, s) = \rho(p, s)[u(p, s) - u_0]$ where ρ is graduation probability and $[u(p, s) - u_0]$ is the college salary premium. We specify the former as a flexible polynomial and the latter as a Cobb-Douglass production function:

$$(30) \quad \rho = \beta_0 + \beta_1 p + \beta_2 p^2 + \beta_3 s + \beta_4 s^2 + \beta_5 ps + \varepsilon_\rho$$

$$(31) \quad \log(u - u_0) = \alpha_0 + \alpha_1 \log(p) + \alpha_2 \log(s) + \varepsilon_u$$

The interpretations of ε_ρ and ε_u are as measurement error in the outcome variable due to finite sampling of students within a given school. We have 1152 observations of ρ based on an average within-school sample size of 756, while for u we have 530 observations with an average within-school sample size of 12. Equations 30 and 31 are both estimated via weighted least squares (i.e., placing more weight on observations with lower variances), using the college-level covariates $\{\rho_l, \omega_{\rho l}, u_l, \omega_{ul}, p_l, S_{0.5, l}\}_{l=1}^L$, where weighting variables $\omega_{\rho l}$ and ω_{ul} represent the adjusted cohort size and the within-school 10-year salary sample size, respectively. In addition, we estimate $\rho(p, s)$ by constrained least squares to ensure that probabilities do not exceed 1.²⁸

²⁸The lower constraint $\rho(p, s) \geq 0$ was never binding in the data, but in principal, this constraint could be imposed as well.

C.2.3. *Two-Stage Estimation Procedure.* The college market estimator consists of the following three-step process:

Preliminary Stage:

- (1) Estimate the minority mass from college-level data:

$$\hat{\mu} = \frac{\sum_{u=1}^U M_u}{\sum_{u=1}^U M_u + N_u}$$

- (2) Estimate boundary-corrected kernel densities and distributions for the distribution of seats for each demographic group: $\hat{Q}_j(p), j \in \{\mathcal{M}, \mathcal{N}\}$
 (3) Estimate boundary-corrected kernel densities and CDFs for investment by each groups from SAT data: $\hat{g}_j(s)$ and $\hat{G}_j(s), j \in \{\mathcal{M}, \mathcal{N}\}$

Estimation Steps

- (1) Estimate $\hat{\tilde{S}}(s) = \hat{G}_{\mathcal{N}}^{-1} \left[\hat{Q}_{\mathcal{N}} \left(\hat{Q}_{\mathcal{M}} \left[\hat{G}_{\mathcal{M}}(s) \right] \right) \right]$
 (2) Estimate regressions 30 and 30 to obtain \hat{U}
 (3) Estimate the cost curvature parameter by dividing (i) the first order condition for the agent of type $\bar{\theta}$ that chooses \underline{s} by the indifference condition (Equation 29):

$$\hat{v} = \frac{\hat{U}_p(p, \underline{s}) \hat{P}_{\mathcal{N}}(\underline{s}) + \hat{U}_s(p, \underline{s})}{\hat{U}(p, \underline{s})}$$

- (4) Estimate types for each s in the sample using the first order condition:

$$\hat{\theta}_j(s) = \frac{\hat{U}_p(p, s) \hat{P}_j(s) + \hat{U}_s(p, s)}{\hat{v} e^{\hat{v}(s-\underline{s})}} \text{ for } j \in \mathcal{M}, \mathcal{N}$$

- (5) Estimate boundary-corrected kernel densities for cost type distributions

APPENDIX D. COMPARATIVE STATICS OF THE LIMIT MODEL

Our goal in this section is to identify conditions under which encouragement and discouragement effects occur in our model. Discouragement effects describe situations wherein competition within a contest intensifies, which causes low ability competitors to exert less effort while at the same time high ability competitors work harder. Since affirmative action schemes (most notably admissions preference schemes) in effect make minority students better competitors, one might expect discouragement effects within the non-minority students. In addition, there will be a symmetric *encouragement effect* within the minority student population.

Our notion of changing competition is captured by examining changes in the distribution of the types of competitors that can be ordered using a single crossing condition applied to the density functions of the relevant distributions.

Definition 4. *Two functions $g(\theta)$ and $h(\theta)$ satisfy the strict single crossing condition (SCC) when for any $\theta > \tilde{\theta}$ we have $g(\tilde{\theta}) \geq h(\tilde{\theta})$ implies $g(\theta) > h(\theta)$. We denote this relation $h <_{\text{SCC}} g$*

Keeping in mind that students with low values of θ choose higher levels of human capital, if f_1 and f_2 represent distributions of student types, then $f_1 <_{\text{SCC}} f_2$ implies that f_1 represents a stronger student population.

Now we turn to our analysis of the discouragement effect. We first consider a color-blind admission policy and analyze how students react to changes in the distributions of types of the other students. Our first result implies a form of the discouragement effect. When there are more high ability students (and hence more fewer ability competitors), the lowest ability students make lower investments in human capital.

Theorem 11. *Consider two population cost distributions, $F_1(\theta)$ and $F_2(\theta)$, that have full support over $[\underline{\theta}, \bar{\theta}]$. Assume $f_1(\theta) <_{\text{SCC}} f_2(\theta)$. Under a color-blind admissions policy, there exists a point θ^* such that $\sigma_1^{cb}(\theta) < \sigma_2^{cb}(\theta)$ for each $\theta \in (\theta^*, \bar{\theta})$.*

Proof. In the color-blind admissions scheme, we need not differentiate between the minority and non-minority students. Furthermore, I will drop the “cb” superscript for notational ease. Denote the equilibrium strategies under F_1 and F_2 by σ_1 and σ_2 , respectively. Note that since the distributions of types are different, the school allocated to each type in equilibrium will also depend on the distributions F_1 and F_2 , and we denote the associated assignment functions as P_1 and P_2 .

Using the notation of a revelation mechanism, the FOC is now

$$U_p(P(\theta), \sigma_i(\theta), \theta)P'_i(\theta) + U_s(P_i(\theta), \sigma_i(\theta), \theta)\sigma'_i(\theta) = C_s(\sigma_i(\theta), \theta)\sigma'_i(\theta)$$

We can rewrite the first order condition as

$$\sigma'_i(\theta) = -\frac{U_p(P_i(\theta), \sigma_i(\theta), \theta)f_i(\theta)}{f_{\mathcal{P}}(1 - F_i^{-1}(\theta)) [C_s(\sigma_i(\theta), \theta) - U_s(P(\theta), \sigma_i(\theta), \theta)]}$$

For the lowest ability student, $\theta = \bar{\theta}$, we can write

$$(32) \quad \sigma'_i(\theta) = -\frac{U_p(\underline{p}, \underline{s}, \bar{\theta})f_i(\bar{\theta})}{f_{\mathcal{P}}(\underline{p}) [C_s(\underline{s}, \bar{\theta}) - U_s(\underline{p}, \underline{s}, \bar{\theta})]}$$

where we use the fact that $P(\bar{\theta}) = \underline{p}$, and we have the boundary condition $\sigma_i(\bar{\theta}) = \underline{s}$ for $i = 1, 2$. The SCC implies $f_1(\bar{\theta}) < f_2(\bar{\theta})$, so equation 32 implies $\sigma'_2(\bar{\theta}) < \sigma'_1(\bar{\theta}) < 0$. This in turn means that $\sigma_1(\theta) < \sigma_2(\theta)$ within a neighborhood of $\bar{\theta}$ by differentiability (recall also that σ_j is strictly *decreasing* and rises in the leftward direction from the boundary point). \square

Our second result provides a condition under which there is at most one crossing-point between σ_1^{cb} and σ_2^{cb} . If there is no crossing point, then all of the students increase their human capital choices under F_1 . If there is a crossing point, then we see both an encouragement and a discouragement effect. In other words, high cost students choose higher levels of human capital, while low cost students acquire less human capital, and

the gap between the best and worst students contracts. Our proof proceeds by ordering the slope of the equilibrium strategy as function of the underlying primitives.

Theorem 12. *Assume all of the conditions of theorem 11 hold. In addition we allow the distribution of seats to be different, and we delineate between the distributions using the notation $F_{\mathcal{P},1}$ and $F_{\mathcal{P},2}$. Assume:*

(33)

$$\frac{U_p(F_{\mathcal{P},1}^{-1}(1 - F_1(\theta)), \sigma_1^{cb}(\theta), \theta) f_1(\theta)}{f_{\mathcal{P},1}(F_{\mathcal{P},1}^{-1}(1 - F_1(\theta))) [C_s(\sigma_1^{cb}(\theta), \theta) - U_s(F_{\mathcal{P},2}^{-1}(1 - F_1(\theta)), \sigma_1^{cb}(\theta), \theta)]} >_{SCC} \frac{U_p(F_{\mathcal{P},2}^{-1}(1 - F_2(\theta)), \sigma_1^{cb}(\theta), \theta) f_2(\theta)}{f_{\mathcal{P},2}(F_{\mathcal{P},2}^{-1}(1 - F_2(\theta))) [C_s(\sigma_1^{cb}(\theta), \theta) - U_s(F_{\mathcal{P},2}^{-1}(1 - F_1(\theta)), \sigma_1^{cb}(\theta), \theta)]} \text{ in } \theta$$

Under a color-blind admissions policy, there exists at most a single point $\theta^* \in (\underline{\theta}, \bar{\theta})$ such that $\sigma_1^{cb}(\theta) < \sigma_2^{cb}(\theta)$ for each $\theta \in (\theta^*, \bar{\theta})$ and $\sigma_1^{cb}(\theta) > \sigma_2^{cb}(\theta)$ for each $\theta \in [\underline{\theta}, \theta^*)$.

Proof. The first part of our result follows the proof of theorem 11 and is omitted. What remains is to show that the point θ^* , if it exists, must be unique.

Suppose there are more than two points where $\sigma_1(\theta) = \sigma_2(\theta)$ and let θ^* denote the largest such point and θ^{**} the second largest. Let $\sigma_1(\theta^*) = \sigma_2(\theta^*) = s^*$ and $p_i^* = P_i(\theta^*) = F_{\mathcal{P},i}^{-1}(1 - F_i(\theta^*))$. Since σ_1 must cross σ_2 from above (recall, $\sigma_1(\theta) < \sigma_2(\theta)$ in $(\theta^*, \bar{\theta})$), the former must have a more negative slope. Combining these facts yields

$$\begin{aligned} \sigma'_1(\theta^*) &= -\frac{U_p(p_1^*, s^*, \theta^*) f_1(\theta^*)}{f_{\mathcal{P},1}(p_1^*) [C_s(s^*, \theta^*) - U_s(p_1^*, s^*, \theta^*)]} \\ &< -\frac{U_p(p_2^*, s^*, \theta^*) f_2(\theta^*)}{f_{\mathcal{P},2}(p_2^*) [C_s(s^*, \theta^*) - U_s(p_2^*, s^*, \theta^*)]} = \sigma'_2(\theta^*) \end{aligned}$$

Note that since $U_{ps} = 0$ we have $C_s(s^*, \theta^*) - U_s(p_1^*, s^*, \theta^*) = C_s(s^*, \theta^*) - U_s(p_2^*, s^*, \theta^*)$. Therefore, it must be the case that

$$(34) \quad \frac{U_p(p_1^*, s^*, \theta^*) f_1(\theta^*)}{f_{\mathcal{P},1}(p_1^*)} > \frac{U_p(p_2^*, s^*, \theta^*) f_2(\theta^*)}{f_{\mathcal{P},2}(p_2^*)}$$

Now we will argue from contradiction that σ_1 and σ_2 can cross at most once. Suppose there were a second point $\theta^{**} < \theta^*$ such that $\sigma_1(\theta^{**}) = \sigma_2(\theta^{**})$. In this case, we would have σ_1 crossing σ_2 from below, which would imply σ_1 is less steep than σ_2 , which would require

$$\begin{aligned} \sigma'_1(\theta^{**}) &= -\frac{U_p(p_1^{**}, s^{**}, \theta^{**}) f_1(\theta^{**})}{f_{\mathcal{P},1}(p_1^{**}) [C_s(s^{**}, \theta^{**}) - U_s(p_1^{**}, s^{**}, \theta^{**})]} \\ &> -\frac{U_p(p_2^{**}, s^{**}, \theta^{**}) f_2(\theta^{**})}{f_{\mathcal{P},2}(p_2^{**}) [C_s(s^{**}, \theta^{**}) - U_s(p_2^{**}, s^{**}, \theta^{**})]} = \sigma'_2(\theta^{**}) \end{aligned}$$

where p_i^{**} and s^{**} are defined analogously. Again, assumption 1 implies $C_s(s^{**}, \theta^{**}) - U_s(p_1^{**}, s^{**}, \theta^{**}) = C_s(s^{**}, \theta^{**}) - U_s(p_2^{**}, s^{**}, \theta^{**})$. For $\sigma'_1(\theta^{**}) > \sigma'_2(\theta^{**})$ to be true, it must then be the case that

$$\frac{U_p(p_1^{**}, s^{**}, \theta^{**})f_1(\theta^{**})}{f_{\mathcal{P},1}(p_1^{**})} < \frac{U_p(p_2^{**}, s^{**}, \theta^{**})f_2(\theta^{**})}{f_{\mathcal{P},2}(p_2^{**})}$$

But this is contradicted by assumption 2. Therefore, σ_1 and σ_2 can cross at most once. \square

The condition required by our theorem is very complex, but much of the complexity is due to the fact that we are allowing more interactions between HC choice, school assignment, and type than the typical contest model. For example, theorem 12 is used in Hickman et al. 2015 to analyze the encouragement and discouragement affect in asymmetric contests.

Example 1. (from Hickman et al. 2015) Suppose that agent utility has the form

$$p - s\theta$$

Moreover, assume the prizes are uniformly distributed, in which case equation 33 reduces to $f_1(\theta) >_{\text{SCC}} f_2(\theta)$ in θ .

If we assume merely that the human capital accumulation (or whatever action is taken to compete) is not a productive asset, then equation 33 becomes greatly simplified. In models without productive human capital, whether discouragement effects occur is a function of how the relative density of the competitors of each type and the prizes competed for changes with θ .

Example 2. Suppose that human capital is not a productive asset, but that agents with lower types have a stronger preference for better schools as well as having lower costs. For example, assume that $U(p, s, \theta) = p(\bar{\theta} - \theta)$. When we use this utility form in equation 33 we find

$$(35) \quad \frac{f_1(\theta)}{f_{\mathcal{P},1}(F_{\mathcal{P},1}^{-1}(1 - F_1(\theta)))} >_{\text{SCC}} \frac{f_2(\theta)}{f_{\mathcal{P},2}(F_{\mathcal{P},2}^{-1}(1 - F_2(\theta)))} \text{ in } \theta$$

For example, this condition would be satisfied if economy 1 (relative to economy 2) had more high cost students and a relatively small proportion of low quality colleges. Such a situation incentives high HC accumulation from high cost students since (1) small increases in HC allows the students to leap in front of a large number of peers and (2) the small number of low quality colleges means such a leap results in placement in a much better college.

In summary, although we can make strong statements regarding the discouragement effect amongst the lowest ability college students, it is difficult to say much about higher ability students without detailed knowledge of the distribution of college qualities even under relatively strong assumptions regarding the distribution of college qualities. If we further assume that human capital is a productive asset, then the picture becomes even more complicated.