College-major choice in Gaokao mechanism

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Econ 605 term paper

1 Introduction

The Chinese college admission mechanism, colloquially referred to as "Gaokao," is one of the few that offers a viable way for ordinary families to climb the social ladder. This topic has consistently attracted significant interest from both Chinese students and their families.

Historically,Gaokao has undergone a significant reform, transitioning from sequential mechanism to parallel mechanism. In the former mechanism, which is similar to the Boston mechanism, students have incentives to prioritize a more secure first choice, as opting for an oversubscribed school in their first choice may lead to an unfavorable outcome. The parallel mechanism was developed in response to the phenomenon that "a good score is not as good as a good strategy" (Nie, 2007)[7], which contradicts the meritocratic nature of Gaokao in selecting the most capable (i.e. high-scoring) students. On the other hand, the parallel mechanism constructs an algorithm that approximates Serial Dictatorship, which can be interpreted as a strict ordering of the students from high to low scores, with the first choosing her favorite and the following ones choosing her favorite from the rest.

The literature on school choice, both classic and contemporary, is extensive, and some of the characteristics of Gaokao admission mechanisms have been covered in these studies. The student-proposing deferred acceptance algorithm (DA) has become the most popular mechanism for school admissions worldwide because of its excellent properties of ensuring the eliminated justified envy and prompting students to truth-telling (Gale & Shapley 1962[8]; Sönmez 2003[9]). Furthermore, considering the reality that schools might be indifferent between many students (particularly at the stage of providing compulsory education, such as primary and secondary schools), CADA (choice-augmented DA) was proposed by Atila et al. (2015)[10]. This mechanism is based on the assumption that students have a strong desire for a particular school. It accomplishes this by eliciting the students' "target" school when they submit their preference lists.

In practice, the devil may be in the details, as there are implementation details in Gaokao that fall outside the standard school choice framework. Chen and Kesten (2016)[5] find that the parallel mechanism should be viewed as a kind of intermediate mechanism between the Boston mechanism and DA, as the matching center limits the number of proposals that students can make and set up multiple rounds of admissions. As the number of proposals increases, the parallel mechanism becomes closer to DA, that is, more stable and less manipulable.

However, the previously mentioned studies neglect to address a significant part of the Gaokao mechanism: students do not merely choose colleges, but concurrently consider the majors they aspire to enroll in. Despite the ongoing reform at prestigious colleges such as Tsinghua University, which is shifting from college-major choice to college-then-major choice, thereby freeing students from considering specific majors when submitting preferences, the admission mechanism of school-major as the basic unit of preference list has been in place for many years, and students and parents have adopted entrenched habits of thinking (Ma et al 2023)[6]. In addition, the range of the reform is limited since many middle-level colleges (211 colleges and below) adhere to the traditional system. Consequently, students with middle or lower scores are even more unlikely to be influenced by this reform.

This paper puts forward the hypothesis that students' college-major choices exhibit similarity to three-sided matching. In the process of extending the framework of two-sided matching to three-sided matching, challenging scenarios have been encountered. It has been shown that stable matching may not exist in three-sided matching (Alkan 1988)[12].However, stability could emerge if the preferences of agents are under some constraints. For instance, Danilov (2003)[3] discovered that if the preference is lexicographic, a multi-sided stable matching could be constructed by multiple layers of two-sided stable matching. But if the lexicographic preference is relaxed to the separable preference, additional constraints are necessary to ensure the existence of a stable matching (Lahiri 2007)[2].

2 Model: college-major-student triple

This paper first reduces the students' college-major choice to a 1-1-1 three-sided matching problem. Intuitively, each school can be categorized into multiple positions, awarding each student one type of diploma. Each major can also be divided into multiple seats, awarding each student one type of qualification certificates. The 1-1-1 matching problem contains three sets, which we assume include n agents respectively. Students: $S = \{s_1, s_2, ..., s_n\}$, Colleges: $C = \{c_1, c_2, ..., c_n\}$, Majors: $M = \{m_1, m_2, ..., m_n\}$. Then, $(s, c, m) \in S \times C \times M$ is a college-major-student triple.

It is assumed that students' preferences $\succeq_s$ over the sets of pairs $(c, m) \in C \times M$ as complete, transitive, strict and separable.

Definition 2.1. Preference $\succeq_s$ is **separable** if $(s, c, m) \succeq_s (s, c, m')$ implies $(s, c', m) \succeq_s (s, c', m')$.

Then, for each student $s \in S$, the ordered preference list $P(s)$ could be divided into two (strict) preference lists $P_C(s)$ and $P_M(s)$, which are over set of $C \cup \{s\}$ and $M \cup \{s\}$ respectively. Each $c \in C$ has a strict preference list $P(c)$ on the set $S \cup \{c\}$ and similarly for each $m \in M$, a strict preference list $P(m)$ over the set $S \cup \{m\}$. Denote $\mathbf{P}$ the set of preference lists of all agents.
$\mathbf{P} = \{P_C(s_1), ..., P_C(s_n); P_M(s_1), ..., P_M(s_n); P(c_1), ..., P(c_n); P(m_1), ..., P(m_n)\}$

It is important to note that some pairs (c, m) might not be feasible due to inherent limitations. For instance, it is possible that polytechnic schools may not offer humanistic majors. Denote $F \subseteq C \times M$ as the set of feasible college-major pairs. A triple (s, c, m) is said to be feasible if $(c, m) \in F$. Also, denote $F(c) = \{m \in M | (c, m) \in F\}$, $F(m) = \{c \in C | (c, m) \in F\}$.

Now we could describe the college-major-student problem as $(S, C, M; \mathbf{P}, F)$.

Definition 2.2. A **matching** $\mu \subseteq S \times C \times M$ is a mapping onto a set of feasible triples (s, c, m) such that if for any two different triples $(s, c, m) \in \mu$ and $(s', c', m') \in \mu$, $s \neq s'$, $c \neq c'$,$m \neq m'$ must be satisfied.

Assume μ is a matching in the college-major-student problem, then denotes $\mu_S = \{s \in S | (s, c, m) \in \mu\}$; $\mu_C = \{c \in C | (s, c, m) \in \mu\}$;$\mu_M = \{m \in M | (s, c, m) \in \mu\}$ and $\mu_{S \times C} = \{(s, c) \in S \times C | (s, c, m) \in \mu\}$;$\mu_{S \times M} = \{(s, m) \in S \times M | (s, c, m) \in \mu\}$;$\mu_{C \times M} = \{(c, m) \in C \times M | (s, c, m) \in \mu\}$.

Let μ be a matching of college-major-student problem. A feasible triple $(s, c, m) \notin \mu$ is called a blocking of matching μ if the following conditions are satisfied:

1. If $(s, c) \notin \mu_{S \times C}$, then $s \succ_c \mu_S(c)$ and $c \succ_s \mu_C(s)$.
2. If $(s, m) \notin \mu_{S \times M}$, then $s \succ_m \mu_S(m)$ and $m \succ_s \mu_M(s)$.

Definition 2.3. A matching μ of college-major-student problem is **stable** if there exists no blocking pairs of μ.

2.1 Case 1:$F = C \times M$

This paper begins by assuming that all (c, m) could form feasible pairs, which does not fully correspond to reality but at least explains the case of comprehensive universities offering all majors. Hence, the three-sided problem could be divided into two one-to-one matching problem. One is the matching between students and colleges $\{S, C; P_C(S), P(C)\}$, the other is the matching between students and majors $\{S, M; P_M(S), P(M)\}$. Subsequently, a stable matching for the original three-sided problem could be identified through the stable matchings of the two one-to-one matching problems.

Theorem 2.4. For original problem $(S, C, M; \mathbf{P}, F)$, if $\mu_{S \times C}$ is the stable matching of the college-choice problem $\{S, C; P_C(S), P(C)\}$, and $\mu_{S \times M}$ is the stable matching of the major-choice problem $\{S, M; P_M(S), P(M)\}$, then

$$\mu = \{(s, c, m) | (s, c) \in \mu_{S \times C}, (s, m) \in \mu_{S \times M}\}$$

is a stable matching for the original problem.

proof

Consider any triple $(s, c, m) \notin \mu$ that blocks matching μ. It is either case $(s, c) \in \mu_{S \times C}$ or $(s, c) \notin \mu_{S \times C}$.

For $(s, c) \in \mu_{S \times C}$, it is obvious that $(s, m) \notin \mu_{S \times M}$. Since $\mu_{S \times M}$ is a stable matching by construction, no pairs will block $\mu(S, M)$. That is, either $m \succ_s \mu_M(s) = m'$ implies $\mu_S(m) = s' \succ_m s$ or $s \succ_m \mu_S(m) = s'$ implies $\mu_M(s) =$

$m' \succ_s m$. In this situation (s,c,m) is not a blocking pair of matching μ since the second requirement for a blocking pair is not satisfied.

For$(s,c) \notin \mu(S,C)$, since $\mu_{S\times C}$ is a stable matching where no pairs will block it. Analogously, we could conclude that (s,c,m) is not a blocking pair of matching μ since the first requirement for a blocking pair is not satisfied.

Therefore, μ is stable matching for original three-sided problem.

Two phase DA algorithm

Step 1: Match Students and colleges. Apply Deferred Acceptance algorithm to obtain stable matching $\mu_{S\times C}$.

Step 2: Match Students and majors. Apply Deferred Acceptance algorithm to obtain stable matching $\mu_{S\times M}$.

Step 3: Combine results from above and construct a matching

$$\mu = \{(s,c,m)|(s,c) \in \mu_{S\times C}, (s,m) \in \mu_{S\times M}\}$$

As demonstrated in Theorem 2.4, it is evident that two-phase DA successfully obtains a stable matching for the college-major choice problem.

2.2 Case 2:$F \subset C \times M$

2.3 college-major choice with quota

Now this paper returns to focus on the more realistic college-major choice problem, where each college and each major has a quota that is more than one position. As we know, in the two-sided matching market, a matching μ of the college admissions problem which matches a college c with students in $\mu(c)$, corresponds to the matching μ' in the related one-to-one market in which the students in $\mu(c)$ are matched in the ranking consistent with the preference list $P(C)$, with the ordered positions of C that appear in the related one-to-one market. That is, if s is c's most preferred student in $\mu(c)$,then $\mu'(s) = c_1$, and so forth. Analogously, since we can think of the college-major choice as students matched to colleges and majors respectively, we can also construct the corresponding $\mu'_{S\times C}$ and $\mu'_{S\times M}$. Now if s is c's most preferred student in $\mu_{S\times C}(c)$,then $\mu'_{S\times C}(s) = c_1$, and so forth.

Proposition 2.5. A matching of the college-major choice problem is stable if and only if the corresponding matching of the related 1-1-1 problem is stable.

3 Gaokao mechanism as two-tier hierarchical matching

3.1 model setup

$S = \{s_1, s_2, ..., s_n\}$: Students

$\mathcal{G} = \{(c,m)\}$: Set of college-major groups, where c denotes colleges and m denotes majors.

$M_g = \{m_1, m_2 ..., m_k\}$: set of majors offered by g;

$\mathcal{M} = \cup_{g\in\mathcal{G}} M_g$:set of all majors across all groups.

q_g: capacity of group g, satisfying $q_g = \Sigma_{m \in M_g} q_m$
q_m :capacity of major $m \in M_g$
P_i : student i's strict preference ranking over groups g
$P_{i,g}$: student i's strict preference ranking over majors $m \in M_g$
π_g: priority order of group g over students.
π_m: priority order of major m over students.

First-tier matching:

A matching $\mu_1 : S \cup \mathcal{G} \to S \cup \mathcal{G}$ assigns each student i to a group g or leaves them unassigned. For each $s_i \in S$, $\mu_1(s_i) \in \mathcal{G} \cup \{s_i\}$; For each $g \in \mathcal{G}$, $\mu_1(g) \subseteq S$ with $|\mu_1(g)| \leq q_g$

Second-tier matching:

Within each group g, a second-stage matching $\mu_g : \mu_1(g) \to M_g$ assigns each student matched to g to a major m. For each $s_i \in \mu_1(g)$, $\mu_g(s_i) \in M_g \cup \{s_i\}$; for each $m \in M_g$, $\mu_g(m) \subseteq S$ with $|\mu_g(m)| \leq q_m$.

3.2 two-tier matching mechanism

First tier: matching students to groups with DA

1. preferences and priorities:

Students submit preferences P_i over groups $g \in \mathcal{G}$. Groups prioritize students based on π_g, which may depend on scores, regional quotas, or other criteria.

2. mechanism

A matching algorithm (DA) is used to assign students to groups: Firstly, each student applies to their most-preferred group; then, each group tentatively accepts up to q_g students based on π_g,rejecting the rest; then rejected students reapply to their next-preferred group.

This process continues until no students wishes to reapply, resulting in a matching $\mu_1 : S \to \mathcal{G} \cup \{s_i\}$.

3. Output of first tier: each student s_i is either matched to a group g or left unassigned.

Second tier: matching students to majors within groups

Once students are matched to a group g, they will be matched to a specific major either on their preference list $P_{i,g}$ or randomly assigned by the gruop authority.

1. Preferences and priorities:

Students submit preferences$P_{i,g}$ over majors; majors prioritize students using π_m which depends on: major-specific Gaokao score requirements and group specific rankings from the first tier.

2.mechanism

Within each group g, the following process is used (DA with intra-group adjustment):

Each student applies to their most-preferred major in M_g; each major m tentatively accepts up to q_m students based on π_m, rejecting the rest; rejected students reapply to their next-preferred major in M_g. This process continues until no student wishes to reapply, resulting in matching $\mu_g : \mu_1(g) \to M_g \cup$

$\{s_i\}$. Moreover, the unmatched students will enter a process called intra-group adjustment, which randomly assigns them to the available seats in the remaining majors. If we assume that students truthfully report their preferences and that their utility of being admitted to programs not on their list is equal to the utility of the unmatched, instability might exist.

3. Output of second tier:

each student matched to gruop g is assigned to a specific major m.

3.3 properties of the mechanism

Stability First tier: the first-tier matching ensures global stability across all groups, i.e. no student-group pair (i, g) prefers such other over their current match.

Second tier: Stability within groups is achieved if no student-major pair prefers each other over their current assignment.

As demonstrated in Section 2, when a student's preference is separable, the two-tier DA algorithm should be able to obtain a stable matching. However, when the student's preference does not satisfy separability and they grow extremely dissatisfied with the result of intra-group adjustment, the Gaokao mechanism will no longer be stable.

Example 3.1.

$S = \{s_1, s_2, ..., s_6\}$

$\mathcal{G} = \{(c_1, m_1), (c_1, m_2), (c_1, m_3), (c_2, m_1), (c_2, m_2), (c_2, m_3)\}$

Suppose $(c_1, m_1), (c_1, m_3), (c_2, m_2), (c_2, m_3)$ all have priority order of $s_1 \succ s_2 \succ ... \succ s_6$ and the remaining 2 programs have priority order $s_1 \succ s_3 \succ s_4 \succ s_6$ Suppose all six students report their true preferences:

Student	True preferences P_i
s_1	$(c_1, m_2), (c_1, m_1), (c_2, m_1), (c_2, m_2)$
s_2	$(c_1, m_1), (c_1, m_3), (c_2, m_2), (c_2, m_3)$
s_3	$(c_1, m_2), (c_1, m_1), (c_2, m_1), (c_2, m_2)$
s_4	$(c_1, m_1), (c_1, m_2), (c_1, m_3), (c_2, m_2), (c_2, m_1), (c_2, m_3)$
s_5	$(c_2, m_2), (c_2, m_3), (c_1, m_1), (c_1, m_3)$
s_6	$(c_2, m_1), (c_2, m_2), (c_1, m_2), (c_1, m_1), (c_1, m_3)$

The matching result will be s_1 matches to (c_1, m_2), s_2 matches to (c_1, m_1), s_3 matches to (c_1, m_3), s_4 matches to (c_2, m_2), s_5 matches to (c_2, m_3), s_6 matches to (c_2, m_1).

It is easy to identify a blocking pair $(s_3, (c_2, m_1))$.

Strategy-proofness First Tier: DA ensures strategy-proofness for students at the group level. Student cannot benefit from misreporting P_i.

Second tier: If DA is used within groups, students are also strategy-proof at the major level. However, strategy-proofness may fail if priorities π_m interact with preferences $P_{i,g}$ in unexpected ways.

Intuitively, students may have incentives to deviate from their true preferences when their preoccupation with enrolling in their desired majors outweighs their commitment to top colleges. This phenomenon arises from the tactics adopted by some students, who, in an effort to avoid intra-group adjustment, deliberately omit their most desired (and often more elite and oversubscribed) college as their first choice.

4 Intra-group adjustment as restricted proposals

Within the framework of gaokao mechanism, the presence of the adjustment option has been known to engender frustration among students. This is due to the fact that it introduces an element of uncertainty and additional stress. A considerable number of students share analogous aspirations: to pursue some average majors at a reputable college, and if rejected, to progress to the subsequent stage and be admitted to some good majors at a middle-quality college. However, the existence of the intra-group adjustment complicates the realization of these aspirations. If students enter the adjustment process at the reputable college and are subsequently accepted into an unsatisfactory major, they may opt to discontinue their college education and repeat senior year in high school. This uncertainty often prompts students to exercise caution and choose options that they perceive as more secure, even if these choices do not align with their true preferences.

This tendency to select conservative options could make the mechanism unstable and less Pareto efficient. Under the adjustment mechanism, students choose secure options out of fear of not getting into their desired program, which may result in some students who would have been admitted to other programs being placed into lower-ranked ones, thus causing an inefficient allocation of resources. Furthermore, the adjustment system can exacerbate the pressure on popular programs or colleges, leading to greater concentration in admissions, while less popular programs may face lower admission rates, further reducing the overall efficiency and stability of the system.

However, the intra-group adjustment is not without its rationale. The fundamental purpose of the adjustment is to impose limitations on the number of proposals that each student could submit. Given the limited processing capacity of computers, if each student were to submit a large number of proposals, coupled with the tens of millions of gaokao participants in China, the college admission process would require a substantial amount of time. To mitigate the challenges posed by this process, the number of proposals is constrained, resulting in a compromise on efficiency and stability.

Example 4.1.

$J = \{(A, p_1), (A, p_2), (B, p_1), (B, p_2)\}$: 4 programs.
Each major of a college has 1 seat: $q_{c,m}$=1
$S = \{s_1, s_2, ..., s_6\}$ six students.
Scores:$f_1 > f_2 > ... > f_6$

Student	True preferences P_i
s_1	$(A, p_1), (B, p_1), (A, p_2), (B, p_2)$
s_2	$(A, p_1), (B, p_1), (A, p_2), (B, p_2)$
s_3	$(B, p_1), (A, p_1), (B, p_1), (A, p_2)$
s_4	$(B, p_1), (A, p_2), (B, p_2), (A, p_1)$
s_5	$(A, p_2), (B, p_2), (B, p_1), (A, p_1)$
s_6	$(A, p_2), (B, p_2), (B, p_1), (A, p_1)$

Restricted Proposal limit:
Each student can only submit their top 2 preferences from P_i
Then, with truthful reporting under a restricted proposal limit, the matching proceeds as s_1 matches to (A, p_1), s_2 matches to (B, p_1), s_3 is unmatched, s_4 matches to (A, p_2), s_5 matches to (B, p_2), s_6 is unmatched.

Blocking pair $(s_3, (B, p_2))$. s_3 prefers (B, p_3) over being unmatched. (B, p_3) prefers s_3 with higher score to s_5 the currently assigned student.

Strategic misreporting of s_2: Suppose s_2 anticipates that s_1 will take (A, p_1). Knowing this, s_2 strategically excludes (A, p_1) from the list and includes (A, p_2) instead. Even if the matching result remains the same after s_2 change the reported preference, the strategy introduces the risk of s_2 failing to match to their true second choice, making the mechanism not strategy-proof because truthful reporting might no longer be optimal.

Why restricted SD is not strategy-proof?

Incentive to exclude risky preferences: students may exclude options they believe will be unavailable based on others' choices, even if those options reflect true preferences.

Forced strategic ranking: Limited proposals force students to prioritize safe options, leading to strategic misreporting. In the example, if s_2 overestimates competition for (A, p_1), they may misreport and end up with less-preferred match.

5 New Gaokao mechanism: without intra-group adjustment

Key features of New Gaokao Admission Rule:

- Flexibility in subject choice: Students select their exam subjects based on the "3+3" configuration, leading to diverse subject combinations C_i.
- Preference list: Students submit a ranked list of preferred college-major combinations. Note that, unlike the old mechanism of submitting college and then the major, each college-major pair can be viewed as an individual unit of program, at which point it is no longer required that the student's preference be lexicographic or at least separable.
- Eligibility constraints: Colleges and majors may require specific subject combinations for eligibility $R_{j,k}$

– Priority Based on Test Scores: Students are ranked by their weighted test scores f_i, with tie-breaking rules based on subject scores or additional criteria.

5.1 Setup

$S = \{s_1, s_2, ..., s_n\}$: Students
$J = \{(j, k)\}$: Set of programs, where j denotes colleges and k denotes majors.
f_i: total score for student s_i
C_i: subject combination of student s_i
$R_{j,k}$: Subject requirements for major $p_{j,k}$
$q_{j,k}$: Each program has a capacity, and each student s_i can submit up to m proposals $m \leq |J|$.

$P_i = \{(j_1, k_1), (j_1, k_2)...(j_2, k_1)...\}$: true preferences about programs
$P_i' \subseteq P_i$:m proposals

5.2 Algorithm

1. Priority ranking:
Rank students by f_i. If $f_i = f_{i'}$, use tie-breaking rules. $\pi(s_1) < \pi(s_2)$ if and only if $f_{s_1} > f_{s_2}$
2. Sequential Allocation:
Process students in order of their priority ranking. Each student s_i selects their top choice from their ranked proposal list P_i that satisfies: Remaining capacity $q_{j,k} > 0$ and subject Requirements $C_i \subseteq R_{j,k}$. Then $q_{j,k} - 1$ if s_i is assigned to $p_{j,k}$
3. Termination: The process ends when all students are assigned or their preference lists are exhausted.

Remark In the event that a student identifies a maximum of m schools as acceptable options, it is optimal for her to submit her true preferences. Conversely, if she identifies more than m schools as acceptable, it is advisable for her to implement a strategy that selects m schools from her preference list and ranks them according to her true preferences.

5.3 Properties

Efficiency: it ensures Pareto-efficient outcomes, as no student can improve without disadvantaging another.

Strategy-Proofness: Students maximize their outcomes by truthfully reporting their preferences.

Higher-scoring students have priority, aligning with the meritocratic principles of gaokao.

Limitations and Potential Modifications:

Preference Clustering: Students may overwhelmingly prioritize top-tier programs, leading to congestion.

This mechanism does not inherently address equity concerns, such as resource imbalances between regions. Maybe regional quotas should be introduced.

5.4 Alternative Mechanisms

New Gaokao Mechanisms with dynamic feedback:

Preference submission: $P_i = \{(j_1, p_{j_1,1}), (j_1, p_{j_1,2})...(j_2, p_{j_2,1})...\}$

Simulation and feedback: for each student, the system simulates admission probabilities for their preferred colleges based on current demand and capacities: $p_{j,k,i} = \frac{q_{j,k}}{n_{j,k,i}}$, where $n_{j,k,i}$ is the number of students ranked higher than s_i who also prefer $p_{j,k}$. Feedback is provided to students, allowing them to revise their preferences if necessary.

Students' beliefs:

Students group colleges and majors into analogy classes based on perceived similarities, such as: Reputation(top tier vs. mid-tier schools); Location: Northern vs. Southern; Historical cutoff scores(similar admission thresholds over recent 3 years). This may lead to misspecification since students overgeneralize, e.g., assuming all top-tier schools are equally competitive.

Students partition colleges and majors into analogy classes $\mathcal{A}_i = \{\alpha_1, \alpha_2, ..., \alpha_K\}$ where$A_k \subseteq J \times P_j$
Within each analogy classA_k, students form expectations $\beta_i(A_k)$ about the average admission probability: $\beta_i(A_k) = \frac{\Sigma_{(j,p_{j,k}) \in A_k} \hat{p}_{j,k}}{|A_k|}$, where $\hat{p}_{j,k}$ is the historical admission rate for college-major$(j, p_{j,k})$.
Objective: Students maximize their utility based on analogical expectations:

$$\underset{R_i', |R_i'| \leq m}{max} \sum_{(j,k) \in R_i'} \beta_i(\alpha(j,k)) \cdot u_i(j,k) \tag{1}$$

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