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Abstract

Although China has made significant strides in science and technology over the past few decades, it faces a variety of challenges in building and cultivating a research ecosystem that fosters innovation. To better understand these challenges, we conducted interviews with 40 Chinese STEM faculty researchers across institutions of higher education in Beijing, Shanghai, Wuhan, and Guangzhou. Interviewees reported that in general there is too much top-down governmental control on China's academic environment. For students, China's college entrance exam, the *gaokao*, incentivizes rote memorization and test-taking at the expense of critical thinking, resulting in a loss of direction and motivation among undergraduates. These were reported to be problems that carry over into graduate school, resulting in students who may work hard and possess strong technical skills, but lack the critical thinking ability required to engage in truly creative research. At the faculty level, interviewees reported that China's evaluation system disincentivizes collaborative, innovative, and long-term research. To meet their contractual publication requirements, interviewees noted that they are often limited to performing short-term research that rewards instant success. In addition, the high cost of living in first-tier cities combined with having an income that is based on the ability to meet one's contractual terms, interviewees noted that researchers may look for ways to supplement their income outside of their academic position, taking time, focus, and energy away from research. We argue that these challenges—both systemic and within the national academic culture—may hinder China's progress to produce the kind of home-grown innovation it has long sought.

Introduction

China is poised to become a world-class innovator. The Chinese government has been actively pursuing an indigenous innovation policy since its *Medium and Long-Term Plan for the Development of Science and Technology (2006–2020)*, initiated in 2006, which called on China to "leapfrog" into positions of leadership in key fields of science, engineering, and strategic technology sectors. The plan pointed to indigenous innovation as having three components: genuinely "original innovation;" "integrated innovation," or the fusing together of existing technologies in new ways; and "re-innovation," which involves the assimilation and improvement of imported technologies. China has thus far focused on the latter two strategies, but is now emphasizing original innovation as it approaches parity in many fields with other technologically advanced countries.

China's subsequent 5-year plans and the controversial *Made in China 2025* plan all echo these ambitions in various ways. They were reaffirmed by China President Xi Jinping at the 10th National Congress of the Chinese Association for Science and Technology (CAST) on May 28, 2021, who emphasized the role of the Chinese Communist Party (CCP), which has long "insisted on placing scientific and technological innovation at the core of the overall national development, and comprehensively planned scientific and technological innovation." Xi stated that "we firmly grasp the strategic goal of building a world power in science and technology," and highlighted the central role of "high-level research universities" in this process, which "should give full play to the advantages of profound basic research and interdisciplinary integration to become the main force of basic research and the new force of major scientific and technological breakthroughs" (Archyde.com 2021).

China clearly has achieved some significant successes:

- The number of China's science and engineering scholarly publications has increased nearly tenfold since 2010. China's total science and engineering output now exceeds that of the United States—China's output is more than double that of the United States in engineering alone. China also now outranks the United States in chemistry (Nature 2020a). While the U.S. citation impact remains considerably higher, the gap is closing (National Science Foundation [NSF] 2020). The Nature Index ranked China second to the United States in 2019, reflecting a 15 percent increase in China's share of publications in 82 high-quality science journals since the previous year. Among the "rising stars" in the index were the Chinese Academy of Sciences—whose share of publications increased 242 percent—and the University of Science and Technology of China (26 percent) (Nature 2020b).
- China's total 2017 research and development (R&D) expenditures were second only to the United States, with China accounting for nearly two-thirds of total global R&D growth since 2000. In 2017, the United States spent $91 billion on basic research—one index of future innovation—compared to $27 billion by China (NSF 2020).
- Preliminary 2019 data indicates that China may have surpassed the United States (Viglione 2020). Much of China's R&D expenditure, however, has been oriented to commercial activities.
- China accounted for nearly half (49 percent) of global patent families organized around unique inventions in 2018, although U.S. inventors accounted for nearly half (47 percent) of United States Patent and Trademark Office patents.

- In some key areas (e.g., robotics, artificial intelligence, quantum computing, biotechnology, digital learning), China may meet its goal of achieving U.S. levels of innovative capacity (Barhat 2018; Deutch 2018; CKGSB Knowledge 2020). In their 2019 report *Research Fronts: Active Fields, Leading Countries,* the Chinese Academy of Sciences and the U.S. firm Clarivate Analytics found that China ranked first in 33 out of 137 research fronts (the United States ranked first in 80). When all 137 research fronts were grouped into 10 broad categories, China ranked first in mathematics, computer science, and engineering; was found to be equal to the United States in ecology and environmental science; and was also strong in physics (CAS-CA 2019).

Yet despite its achievements, Chinese scientists have yet to produce cutting-edge breakthroughs that might receive a Nobel Prize in physics or chemistry, or result in large numbers of innovative, globally competitive products (with certain exceptions). China also remains dependent on foreign technology in crucial high-tech areas, from computer chips to high-level digital control systems to high-level hydraulic components.

The success China has had is due to many factors, including its aggressive state-led industrial policies, which have directed its vast stores of foreign exchange into key research and economic sectors (Appelbaum et al. 2018). Higher education has been a key target of significant investment, particularly elite institutions in Beijing, Shanghai, and Guangzhou. In the late 1990s, the central government implemented Project 211 and 985 in order to build and transform its higher education institutions into comprehensive research universities and become world-class university candidates. These projects, ending in 2016, were succeeded by the current Double World-Class Strategy to propel its higher education institutions to become "world-class universities with Chinese characteristics" (State Council 2015; Zhong et al. 2019). These

government initiatives provided tremendous financial and human resources and propelled elite universities into top international global rankings. In 2016, China produced 1.7 million undergraduate science and engineering degrees, more than twice the number of the United States, and 32,000 doctorates in natural sciences and engineering, also surpassing the United States (with 30,000) (NSF 2020). According to the Nature Index (Nature 2020c), the world's top ranked institution in terms of high-quality publications in 2019 was the Chinese Academy of Sciences (Harvard ranked second). Five Chinese universities were among the top 20: the University of Science and Technology China (ranked 8th), Peking University (10th), Tsinghua University (12th), Nanjing University (13th), and University of Chinese Academy of Sciences (14th). All of the Chinese universities had moved up in the rankings since the previous year. Yet as we shall see, the higher education system also faces challenges that may impact China's efforts to promote original innovation.

The circulation of Chinese students and faculty through high-quality foreign universities—and the effort to bring them back through financial incentives administered through a dozen different "talents" programs (Cao et al. 2020)—has had a clear impact on China's growing prominence in high-quality scientific publications. As of 2017, some 5.2 million Chinese had studied abroad, with most earning BAs and MAs in science, technology, engineering, and mathematics (STEM) fields (Cao et al. 2020). The United States has been the principal target for Chinese students at all levels, with 373,532 Chinese students studying in the U.S. in 2019–2020, accounting for 35 percent of all foreign students (Open Doors 2020). During the 2018–2019 academic year, there were an estimated 76,100 Chinese graduate students in STEM-related fields in U.S. universities—nearly one out of every six STEM graduate students. These included 40,500 in M.A. programs, and 35,600 earning PhDs (Feldgoise and Zwetsloot

2020)—a decline from the estimated 40,000 earning STEM-related PhDs in 2016 (NSF 2020), possibly reflecting the efforts taken by the Trump administration to prevent Chinese nationals from studying in the United States on national security grounds (U.S.-China Economic and Security Review Commission 2019; Anderson 2020; Wong and Barnes 2020).

The most detailed study to date found that Chinese scholars who studied or worked abroad had higher impact publications than those who had not—partly because of the networks they had cultivated, which provided opportunities for continued international scientific collaboration and co-authorship. Such collaborations fostered advances in science and were mutually beneficial for both China and its partners. The authors conclude that "the mobility (in and out) of foreign-bound students and scientists has had a major impact on the development of both the Chinese science system and the global science systems" (Cao et al. 2020). In our previous research, we also found that returning students and faculty played a role in encouraging greater risk-taking and challenging assumptions—skills they acquired in foreign universities but which were often absent in Chinese lab settings (Appelbaum et al. 2018; Han and Appelbaum 2018).

It remains an open question whether the benefits of such circulation will remain, given the tension between the United States and China. During its first hundred days, the Biden administration appeared to be continuing the Trump administration's adversarial approach toward China. The Senate Foreign Relations Committee approved the Strategic Competition Act of 2021, reflecting bipartisan agreement on the need to aggressively counter China. Yet at the same time, the Biden Administration lifted COVID-era travel restrictions on Chinese students. It remains too early as of this writing (June 2021) to know how U.S. policy will affect the ability of Chinese STEM students to study in the United States.

In our previous publication on China's higher educational system, we identified a number of challenges that must be overcome if China hopes to realize its ambitious science and technology (S&T) goals and original innovation ambitions. That research was based on an online survey of STEM faculty from China's top 25 universities, conducted in three waves in 2015. The survey resulted in 731 respondents, of which 96 percent had PhDs, and 17 percent had degrees from abroad (survey methodology and results are discussed in detail in Han and Appelbaum 2018).

We found that the biggest challenge, reported by 37 percent of all respondents, was that China's current research ecosystem promoted short-term thinking and instant success, emphasizing publication quantity over quality. This, we learned, discouraged innovative and original research, instead encouraging researchers to go after "low-hanging fruit" rather than engaging in long-term, innovative, and potentially riskier research. Research funding was another widely shared concern, reported by 33 percent of respondents. While complaints about inadequate funding were common (a complaint hardly unique to China), 9 out of 10 respondents raising the issue of funding complained that personal connections—*guanxi*—played a key role in funding success. Nearly as many respondents (31 percent) complained about excessive bureaucratic or governmental intervention in academic affairs. Specifically, survey respondents were concerned about overly rigid, top-down requirements stifling academic freedom; pressure to follow official ideologies and standards; pressure to focus on externally set research areas; and excessive power of administrators and bureaucrats who lack expertise in what they oversee.

While the survey provided a snapshot of respondents' perceived challenges, to obtain a more in-depth sense of their experiences we followed up by conducting 40 face-to-face interviews with Chinese STEM faculty researchers at Tsinghua, Peking, Fudan, and other major

universities that had survey participants who expressed a willingness to be interviewed in person. The interviews were conducted in June 2015 and May 2016 in the midst of higher education policy changes and Xi's anti-corruption campaign. In this paper, we report on the results of those interviews, in order to better understand the strengths and weaknesses of China's academic STEM research ecosystem.

Methods

Follow-up Interviews

Of the 731 individuals who participated in the survey, 317 (43.4%) indicated they were interested in participating in a follow-up interview and provided their names and contact information. Based on timing and availability, interested individuals from universities based in Beijing, Shanghai, Wuhan, and Guangzhou were contacted. The first round of follow-up interviews (N = 16) was conducted from June 22–July 1, 2015, and a second round (N = 24) from May 13–28, 2016 for a total of 40 interviews.

Because of the sensitive nature of the topics discussed in the interviews, we are providing only aggregated descriptions of the interviewees to maintain their confidentiality, anonymity, and to reduce the probability that they might be identified. Several interviewees noted that because they have been outspoken on some of the issues discussed in this study, their identities could be guessed if their department or university were associated with their statements. Consequently, we refer to interviewees only by their academic rank and the city in which their university is located. Human Subjects Approval for the 2015 survey and the follow-up interviews was granted by the University of California, Human Subjects Committee, Office of Research, Santa Barbara.

In total, 10 interviews were conducted with faculty researchers across different disciplines at Shanghai Jiaotong University; 8 at Huazhong University of Science and Technology; 7 at Sun Yat-Sen University; 4 each at Wuhan University and South China University of Technology; 3 at Peking University; 2 at Tsinghua University; and 1 each at Renmin University of China and Beijing Normal University. Of the 40 interviewees, 21 (53%) held an academic rank of professor at the time of interview; 17 (43%) were associate professors; 1 was an assistant professor (2%); and 1 was unknown (2%). Numerous STEM disciplines were represented by the interviewees, including agriculture and biology; biomedical engineering; chemistry and chemical engineering; computer science; electronic information; environmental science and engineering; geography; life sciences; manufacturing; materials science; mathematics; mechanical engineering; medical sciences; physics and astronomy; psychology; public health; and systems science.

A semi-structured interview approach was used in which all participants were asked about China's higher education research ecosystem; the evaluation system for faculty researchers; the education system; and the role and impact of the central government on STEM research in China. These areas were identified as topics for more in-depth research and analysis based on the free responses provided by survey respondents from the 2015 study. All interviews were conducted in Mandarin Chinese and translated into English.

Qualitative Analysis

Interviews were analyzed using NVivo 10, a qualitative data analysis software. For consistency, two of the authors (XH and IL) read and coded all of the interviews. After reviewing all of the interviews in depth, seven themes were identified and used as parent nodes for coding: *Chinese education systems*; *Chinese research culture*; *differences between China and*

international systems; *research faculty institution of higher education working conditions*; *research funding*; *role of central government in China's academic or research ecosystem*; and *views on Chinese talent programs*. NVivo defines a node as a collection of references about a specific theme, case, or relationship (NVivo 2020). Five of the seven parent nodes consisted of sub nodes (also termed child nodes in NVivo) that allowed further clarification of the parent node. Explanations of the relationship between the child and its respective parent node, as well as when interviews are coded for each node are detailed below. Please note that an excerpt or statement could be coded under multiple nodes as many of these topics are interrelated.

The parent node *Chinese education systems* consisted of three sub nodes: *K-12 education*; *undergraduate education*; and *graduate education*. Interview excerpts were coded under *Chinese education systems* if they referred to any aspect of China's education system from K-12 to higher education. Excerpts were coded under *K-12 education* if they referred specifically to the K-12 education system in China including any mentions of the *gaokao*, the Chinese college entrance exam. Excerpts were coded under *undergraduate education* if they referred to any aspect of China's undergraduate education system including what students do with their undergraduate degree after they graduate. Lastly, excerpts were coded under *graduate education* if they referred to any aspect of China's postgraduate system including both Master's and PhD programs as well as what students do after they receive their postgraduate degree.

Interview excerpts were coded under the parent node *Chinese research culture* if they referred to any aspect of the research culture, including collaborations, plagiarism, innovation, China's S&T future, research quality, scientific integrity, research funding, and workload balance between research and teaching.

The parent node *differences between China and international systems* consisted of two sub nodes to differentiate differences in the *education systems* and those in the *research systems*. Excerpts coded under differences in *education systems* referred to how China's approach to teaching and pedagogy in K-12 as well as higher education differed from Western education systems, primarily from those of the United States and Europe. Excerpts coded under *research systems* included differences in how graduate students are mentored; departmental and university expectations of graduate students and research faculty; salary; and motivations behind research.

Interview excerpts coded under the parent node *research faculty institution of higher education working conditions* referred to statements about how research faculty are evaluated by their department or university, and salaries. Statements related to how research funding is acquired, where and who provides funding opportunities, and the role that human connections (i.e., *guanxi*) play in obtaining funding were coded under the node *research funding*.

The node *role of central government in China's academic or research ecosystem* included any statement referring to the role, impact, or influence that China's central government has on China's education from K-12 to higher education or how research is conducted at institutions of higher education. Statements referring to the benefits, challenges, or impacts of China's talent programs were coded under *views on Chinese talent programs*.

Excerpts coded under each node were then synthesized to identify commonalities as well as differences across interviewees.

Results

A semi-structured interview approach was used, and not all interviewees were asked the exact same questions. Instead, we asked interviewees to elaborate on their chosen area of focus within each topic of interest (e.g., China's higher education research ecosystem; the evaluation

system for faculty researchers; the education system overall; the role and impact of the central government on STEM research in China). As a result, some topics were discussed more than others. We have highlighted notable viewpoints below. This reflects the interviewees chosen areas of emphasis and does not necessarily indicate unanimous agreement or disagreement among interviewees regarding these topics.

Role of the Central Government and Research Funding Structures

All 40 interviewees provided comments on the role of the central government on China's STEM ecosystem, including research funding. Interviewees focused on the control and impact of the Ministry of Education (MOE) on the general research and regulatory environment and the efficacy and fairness of specific MOE policies, especially the quota of graduate students as well as the efficacy and fairness of research funding structures. Some interviewees also mentioned the inequalities between different universities and different regions and Xi's anti-corruption campaign on the research ecosystem.

<u>The MOE's General Control and Influence over the Research Environment</u>

The most commonly discussed theme in the interviews was the high-level of control and planning on the S&T research ecosystem coming directly from the MOE, with 21 separate interviewees commenting on the issue. Eighteen of the 21 interviewees believed that the central government is too controlling, while 3 interviewees thought that the central government had the right level of control and was not overly controlling.

The main issue brought up by interviewees was that the MOE controls too many elements of the research ecosystem, and many of these elements do not need to be controlled by such a high authority. There were multiple comments of how government interventions are inefficient and sometimes even counterproductive. One of the specific policy examples was the control on

the number of admitted graduate students, explicated in a following section. One interviewee commented specifically about the limits of top-down institutional change—that even though certain policy aspirations are important, certain institutional changes must come naturally, from the bottom-up. Instead of fostering independent capabilities and positive trends within the research community, the government takes a very paternalistic approach, as described by two different associate professors in Beijing:

> *[The MOE] tries to controls things that don't need to be controlled, or trying to control things that are useless, so in the end, they miss the mark on controlling things that need to be changed or improved. But, they may do this because these are the only things they can actually control. The government treats the research community like how a nanny treats children in China.*

> *The government should just give up control—things will happen naturally, it's a natural process. If you give a system enough freedom, things will naturally figure itself out. It's hard to figure out reforms that will solve everything, you have to let the system solve itself. The Chinese government has a father-child relationship with its people—it feels like it needs to guide its children [its citizens] in order for the child to succeed, the government feels like it knows best.*

For many, the issue of strict control is not isolated at the central government level. The overbearing control begins at the MOE level and precipitates down through the universities and departments, creating a less than ideal environment for research and innovation for the 18 interviewees. An associate professor from Shanghai elaborated on the extreme level of control in universities:

You have people in Chinese universities that control everything—your emotion, your well-being, your activities—they hire people to do all of this for students. We have approximately 900 professors, but we have like 10,000 staff members. You have tons of administration, all over the place, for everything—there's too much control. You have offices controlling everything—controlling collaborators, controlling everything in China.

Interviewees also provided suggestions on how to improve the issue of MOE control, mostly underlining that the decision makers should not be the central government. Four interviewees believed that universities should receive more autonomy and flexibility to be able to dictate their own policies. Three other interviewees noted that experts, leaders in the scientific disciplines and education sector, should be in charge because they work on these educational and research ecosystem issues on a daily basis. Four interviewees argued that professors should have a larger impact in creating policy and that, currently, they have very little power or control. In addition, eight interviewees mentioned the importance of academic freedom and autonomy. Interviewees commented that research is primarily driven by funding rather than what faculty actually want to research. Among the eight interviewees, only one mentioned contentment with their current autonomy and ability to conduct the research they want.

Three of the 21 interviewees believed the central government was not too controlling. One interviewee explained that top universities have a lot of flexibility because the government allows for policy experiments among these elite institutions, reflecting the government's tendency for incremental reform rather than comprehensive reform. Several interviewees also qualified the high degree of control. One interviewee pointed out that this high degree of control from the MOE may be necessary because university administrators may not have better or sufficient management skills either. Five interviewees highlighted that the high degree of control at universities in China has dramatically improved the research quality under the results-oriented

evaluation schema of the MOE, catching up to elite international universities. As one associate professor in Beijing stated:

> *The government is able to push things through so this is probably its best asset—if the Chinese government is set on doing something, then we will see results very fast and very good results. Programs such as the 211 and 985 were great in shortening the distance between the quality of research in China and that from abroad. By shortening this distance, we can finally start competing in the international arena and start encouraging others to come back. Before these programs, we didn't have anything to offer.*

Graduate Student Quotas

One of the major areas under the control of the MOE is the quota on the total number of graduate students allowed to be accepted each year. Interviewees explained that the quota on the number of graduate students is first dictated by MOE, providing a quota to each university; universities then dictate quotas for each department; and department leaders then dictate quotas for each professor. The quota is a maximum limit and professors are not required to take any graduate students. Sixteen interviewees commented on this issue, with 8 interviewees noting negative consequences, 5 interviewees noting positive consequences, and 3 interviewees who pointed out both negative and positive consequences. The issue is when professors would like more graduate students than the number they are allowed. Multiple interviewees stated that professors who are able to take on PhD students are allowed, on average, 1 PhD student per year.

A negative consequence of such a restrictive policy on graduate students mentioned by three of the interviewees is that this is not enough graduate students for the increased number of faculty in most departments. In addition, graduate student quotas do not correspond with the funding professors have—some professors who have large amounts of funding are not able to

admit more students whereas other professors without much funding are allowed to admit the same number of students. One interviewee mentioned an anecdote that the MOE can use the graduate student quota to punish universities or departments that have not abided by certain administrative policies (e.g., filling out paperwork on time) by reducing the number of students allowed.

Interviewees also noted positive effects from the quota. Specifically, fairness was mentioned as the primary benefit of having a quota system. Five interviewees indicated that the quota system should not be altered because it would not be fair for certain disciplines with less funding, and that it ensures all professors are able to take on at least one student every year. Universities, departments, and professors with higher rankings and more funding would benefit from eliminating the quota system, but many weaker entities would be hurt. As one associate professor from Guangzhou noted:

> *The good universities (911, 285) have more PhD quotas, but bad departments in good universities may not get any resources. Getting rid of the PhD quota—if students could apply anywhere and go anywhere—the top universities would benefit, and weaker universities would be hurt.*

Some other positive elements of the quota system include that professors are less able to exploit their students or build up a labor force with students. There was also one mention that the quota system has improved the caliber of graduate students—that the quality of students was much lower before the quota system was implemented in 2009 when professors were able to accept an unlimited number of doctoral students.

Research Funding

The last major theme with regard to the role of government relates to the research funding structures within China's S&T ecosystem. Interviewees named three main sources of funding: National Natural Science Foundation (NNSF) of China funding, special funding from national key projects, and funding from industry.

Fourteen interviewees commented that the NNSF has transparent and open guidelines for funding. The funding structure relies on a peer-review system with very few human factors involved, and the trajectory of NNSF funding is a positive one for most researchers. In fact, multiple interviewees contrasted the openness and fairness of NNSF funding with other sources of funding, using NNSF guidelines as the gold standard.

With regard to other government-sponsored funding, interviewees were less positive. Eleven interviewees mentioned how funding for national key projects is not very open. Some of the interviewees were more critical than others, but the consensus is that special funding outside of NNSF is quite restrictive as these funding structures do not allow for open proposals and researchers must possess certain qualifications to even apply for funding. One interviewee mentioned that *most* researchers do not meet the requirements to apply for such special national projects. On top of that, the selection process is not transparent, and one interviewee mentioned that *guanxi* matters more in the context of such funding structures. Lastly, the sustainability and stability of such funding is questionable given that special funding is based on the priorities of the central government. As a professor from Guangzhou noted:

> *One's research depends [on] which way the wind blows—if the government changes, then priorities change, you may lose your funding. This is not a stable environment. This is more for the larger national key projects—not the NNSF, which is more open and transparent.*

The third main source of funding comes from industry, with seven interviewees mentioning the importance of industry funding as a counterbalance to government-sponsored research. Some interviewees stated that industry funding is much more flexible and fills in gaps of research. Others stated that industry funding provides a diversified funding structure that is perhaps better for the overall S&T ecosystem. Two interviewees mentioned that the role of industry in the S&T ecosystem is still developing and that it should take on a larger role in research and research funding in the future to reduce reliance on the central government for progress in S&T.

Outside of funding structures, five interviewees discussed the inequality perpetuated by research funding that echoed the same issue as the overemphasis on rankings. They mentioned the high regional education inequality, with very few resources and education opportunities in the Western provinces. In fact, one professor from Wuhan suggested that the largest issue in China's S&T research ecosystem is educational inequality among regions and should be a top priority for the MOE to resolve. This interviewee also stated that Peking and Tsinghua Universities receive a disproportionate amount of government funding compared to other Chinese universities, and that Beijing and Shanghai receive more government funding than other cities in China, making it unfair and difficult for other institutions and cities in China to catch up to these front-runners.

Lastly, these interviews were conducted soon after General Secretary Xi implemented his large-scale anti-corruption campaign. Eight interviewees discussed how the anti-corruption campaign affected the research ecosystem, with three interviewees acknowledging the positive influence of the campaign, five interviewees objecting to the increased restrictions resulting from the campaign, and two interviewees stating there are both positive and negative effects from the

campaign. The major positive effect of the anti-corruption campaign is that it improved financial efficiency. However, it also created barriers for research-tangential activities such as traveling to conferences, and collaborating. A professor in Wuhan succinctly pointed out these two issues:

> *[The new policies from the anti-corruption campaign] right now [are] overly strict. [The administrators] believe that conferences and, etc. are part of your job as a researcher, so you shouldn't use extra money for these things that you should already be doing. But overall, it's been good because [the anti-corruption campaign] has provided more money for actual research. I think it's a good thing in the sense that they're trying to promote a sense of responsibility and professionalism.*

China's K-12 and Undergraduate Environments

Thirty of the 40 interviewees commented on how the K-12 education system or the undergraduate academic environment negatively impacted China's overall research capabilities. Twenty interviewees commented specifically about the National College Entrance Examination (i.e., the *gaokao*), emphasizing how certain qualities developed in grade school in preparation for the *gaokao* affect the research abilities of university students. Interviewees stated that the *gaokao* system and aspects of the undergraduate environment generates a lack of critical thinking capabilities among students and ill-prepare them to be independent researchers.

Lack of Critical Thinking and Independence in K-12

The most common theme mentioned by interviewees regarding China's primary and secondary education system was how the *gaokao* adversely affects students' critical thinking abilities. Eleven interviewees noted that the *gaokao* tends to produce students who are brilliant test-takers, but are lacking in critical assessment. In general, student evaluation is entirely test-based starting from kindergarten, and especially in middle school and high school in preparation

for the *gaokao*. Interviewees noted that the *gaokao* emphasizes rote memorization, diligent work ethics, and repetitive problem-solving, but it hinders creativity and does not foster individual interests. One interviewee noted how this may provide the general population a strong foundational knowledge, especially in science and mathematics. However, two interviewees noted that not every individual needs such an in-depth knowledge in science and mathematics and argued for diversification of content and activities in class.

Such an academic background is a major issue for students in their undergraduate and graduate studies because students have not developed their own research interests or the capabilities and habits needed for independent research, especially in critical thinking. As one professor from Guangzhou stated:

> *The current system produces students that by the time they get to college, they're a bunch of useless students who are very hard to change. [For example], we tell them that they can't pour chemicals down the drain, but they [still] do it because that's how they have been taught since middle school, and it is very hard to change who they are by the time they get to college. If students are not taught right from the beginning, then it's very hard to correct them later on.*

Ten interviewees also noted how parents and relatives reinforce the negative aspects of the *gaokao* system, revealing the societal problem in China's education system. Interviewees explained that because China has so few good universities and the disparities between the universities are so significant, parents pressure their children to earn perfect grades in test scores in hopes they can attend a top school. As one professor from Guangzhou noted:

> *In China, parents contribute to a lot of problems: they want their kids to all be high achieving and want them to go to the best universities, but there's a natural difference in how intelligent and how much individual people want to learn. You should not push your kids to all be Peking University graduates—not all of them have the ability and that's okay, you look for other avenues for them. We need to have a society where it's okay to have blue collar workers, have scientists, have service workers, etc.—people should do things according to their abilities.*

This parental pressure and *gaokao* also hinder students from developing the ability to think for themselves, as one interviewee from Wuhan stated:

> *The gaokao really takes away students' interest and love of learning. When we ask [students] why they wanted to do [an] honors class, most of them answered "well, because my parents wanted me to."*

In fact, three interviewees mentioned how China's central government is aware of the intense pressure adolescents face regarding the *gaokao*, and has tried to make improvements. Two interviewees provided the example that students are now allowed to take the English section of the *gaokao* twice and have their highest score counted. However, multiple interviewees clarified that major reforms in the education system do not matter, because the *gaokao* system is so entrenched in Chinese society, parents will protest substantial changes to the *gaokao*. A professor from Wuhan aptly described the issue:

> *Because ultimately no parent wants to lose the race, and they won't let up, so everyone is still competing.*

Interviewees also discussed the issue of fairness within the *gaokao* system. Six interviewees believe the *gaokao* is a fair system and merit-based, because it is a standardized test and relies only on numbers—scores and rankings. Two interviewees also stated that the *gaokao* provides an opportunity for students from rural or poorer regions in China to achieve higher education. Most of these six interviewees noted that the *gaokao* system is the "fairest" solution from a variety of substandard solutions; they believe that the *gaokao* is flawed but there is no better way to evaluate such a large population of students.

Three interviewees commented on how the *gaokao* favors children from wealthier backgrounds and children with certain urban *hukou* (i.e., China's household registration system), as the *gaokao* requirements for top Beijing universities are lower for those with a Beijing *hukou* than those with a Jiangxi *hukou* or otherwise. A professor from Beijing believed the *gaokao* system to be unfair even though it is an equal system, comparing it to the driving restrictions in Beijing:

> *For example, there are too many cars in Beijing so they said on Mondays and Wednesdays, if you have a tag that starts with so and so, you can drive-- it seems very fair that people must take turns. But what if you only needed to drive on Wednesday, and are okay with not driving any of the other days. It's not really fair and overall, it doesn't discourage people from driving. So in terms of education, everyone has to walk the gaokao—because there's only the one road, everyone must take this road, there are no alternatives.*

Low Motivations Among Undergraduates

When discussing the undergraduate environment within China, the most common observation among interviewees is the extreme contrast between the intense *gaokao* environment

and the relaxed and easy undergraduate environment. Seven interviewees noted that undergraduate students often lose their direction and motivation in college, because the intensity of the *gaokao* provided direction for their entire life and then students find undergraduate studies in China to be too easy and relaxed. This is also a result of the easy graduation expectations for students. An associate professor from Beijing described the following dilemma:

> *In China, college is much more lax than K-12, students are much more relaxed, and it's much easier than K-12. Everyone graduates from college—there's not much difference [between the top graduate and the worst graduate], because everyone has to graduate.*

Furthermore, the *gaokao* does not prepare students for undergraduate studies, as seven interviewees commented on the lack of critical thinking skills and initiative from their students. Multiple interviewees noted that students do not ask questions in class, and that undergraduate education is still based on rote memorization rather than critical or independent thinking. As one associate professor from Shanghai stated:

> *We, professors and the university, treat them like little kids once they're in college, it's like we're babysitters. We want to give our students more freedom, creative thinking, and independence but this will take time.*

Other Challenges in the Undergraduate Environment

Interviewees also mentioned other challenges in the undergraduate environment that are not conducive to high-quality research at the graduate level. Four interviewees discussed how the current job market in China has affected undergraduate education. Because the job market is so competitive, students cannot get a job without a college degree. One interviewee noted that undergraduate education is utilitarian because students attend college for the sake of receiving a

degree to get a better job rather than to learn or foster intellectual interests. This contributes to the lack of initiative and motivation of students in their undergraduate studies. In terms of post-undergraduate trajectories, four separate interviewees noted that about one-third of undergraduate students go into the workforce after graduation, one-third go abroad for graduate school, and one-third stay in China for graduate school.

Four interviewees also discussed the lack of freedom for undergraduate students. Students do not have many choices in their 4 years of study; their course-load is already pre-set. Two interviewees mentioned that changing majors is quite difficult and involves additional departmental exams. This concerned the interviewees as it could hinder undergraduate students from fostering their true academic and research interests.

The lack of freedom goes beyond academic activities and into daily classroom activities. One interviewee noted that undergraduate students in the United States would have their laptops open and blatantly disregard the lecture, where students in China would not exhibit such behavior.

Another issue brought up by four different interviewees is the deterioration of the quality of teaching in undergraduate courses, which negatively impacts the quality of graduate researchers. Three of the interviewees commented that undergraduate teaching becomes a low priority for professors because of the focus on publication requirements in the faculty evaluation system. Lastly, three interviewees stated that the inequity among undergraduate institutions is a major issue in terms of fairness and overall quality of academic institutions. According to these interviewees, there is an unfair allocation of resources as Beijing and Shanghai universities receive more resources and more funding compared to other universities.

China's Graduate Education Environment

Nearly every interviewee (38) commented on the graduate education system in China, with 24 interviewees discussing the specific requirements for graduate students to complete their studies at their respective institutions. About half of those who shared their institution's requirements (13) also indicated that the existing paradigm (e.g., specific number of publications to graduate) may be in some ways flawed, potentially failing to equip graduate students with the tools to succeed in research (e.g., think critically and independently). Of the 26 interviewees who opined on the quality of graduate students in China relative to the rest of the world, only 2 had positive characterizations—the others thought a majority of graduate students are not well suited for graduate-level research.

Tests Appear Less Helpful Within Graduate Education

The most common theme among the interviewees regarding China's graduate education system was how the "quality" of graduate student—for example, their ability to design and conduct an experiment or think creatively—was generally viewed as inferior to students in other countries like Germany or the United States. While a few simultaneously acknowledged either a strong work ethic or equivalent rote technical skills (e.g., mathematics), 24 interviewees blamed the difference in quality on a general lack of creative, innovative, or independent thinking at the graduate student level. As one associate professor from Beijing noted:

> *In China, graduate students are not very good in quality. Overall, graduate students in China have [a] good work ethic, but in other things – in terms of interest and insight – they're not as good as foreign students.*

For many interviewees, the reliance on graduate entrance exams as a measure of a prospective graduate student's quality, ability, or interest is inadequate and potentially perpetuates the lack of critical thinking and independence associated with the society's focus on

the *gaokao* in K-12 education. Eight interviewees noted that of the two ways a student could enter into graduate school, those that entered based on their test scores were likely less capable than those who were strong-performing undergraduates. As one professor from Guangzhou explained:

> *Students who get high scores on grad exams, they probably weren't great students as undergrads, so their undergraduate scores [wouldn't] get them a good job. So they spend a lot of time and effort to prepare for the [graduate exam] so [that] they can get into the graduate program, but they don't really have ability. Good [undergraduate] students, even if [they] score lower on the [graduate exam] will be better students.*

Specifically, interviewees did not see the value in testing (e.g., "useless," a "waste … of one's time"), in part because many students end up spending a large proportion of their undergraduate time preparing for the test at the expense of, for example, focusing on "creative thinking." One professor from Shanghai simply stated:

> *The [students] who get in by taking the [national] test, they're not so great because they're only good at taking tests [and] not so much on research.*

Although one interviewee admitted that the *gaokao*, while not great, is at least fair, interviewees observed that Chinese graduate students appear to have less passion or self-motivation in the research they are doing compared to students in other parts of the world. Three interviewees specifically mentioned how graduate students may be less focused on the research they are doing and more interested in "chasing a degree" or getting "a better job." In fact, an interviewee from Shanghai thought that only about 10% of Chinese graduate students are truly

interested in the research they are doing, with the rest hoping to leverage a better job with a higher degree:

> *I think this happens because Chinese students are under such high pressure to get into college and pass the gaokao that they don't have any time to think about what they're interested in, what they're passionate about, so what happens when they enter college is that they don't really know what they want to do or what they're interested in. This takes time for them to develop and that's why such a low percentage actually are interested in research.*

Rigid Graduation Requirements and the Student Environment

When discussing the graduate experience for students in China, the most common view interviewees expressed was that the requirements may not be conducive to an environment where graduate students can learn how to think for themselves or discover research questions they are passionate about. Every interviewee who volunteered graduation criteria for their institution essentially shared the same template by which graduation students are evaluated: some specific number and level of Science Citation Index (SCI) publications. One interviewee from Guangzhou shared that because most of their master's students are not qualified to do research, they give those students just enough work so they can publish an adequate number of SCI publications and graduate.

The requirement to publish can potentially add undue pressure or stress on students, which some interviewees blame for driving some students to plagiarize their way to the necessary number of SCI publications. Interviewees shared that students who may be susceptible to cheating, copying, or plagiarizing do so because of the pressure they face to graduate, whether cultural, familial, or both. The pressure may also arise from a lack of adequate undergraduate

preparation in learning how to perform an adequate literature review or designing and performing an experiment, let alone engaging in and writing a discussion. As one associate professor in Shanghai remarked:

> *As long as there is a publication count requirement, [plagiarism] will always be a problem.*

In spite of students engaging in bad behavior (e.g., plagiarism, playing games, watching TV) or outright not meeting standards or performance expectations, 13 interviewees revealed how challenging it is to directly address this with students and how difficult it is to remove a student from the program. One interviewee estimated that approximately 10% of PhD students are kicked out, but felt that the number should be closer to 20%. Another interviewee believed between 80–90% of current PhD students should not graduate. According to some interviewees, one reason that it is hard to remove underperforming students from a PhD program is because the number of graduate students a school may host is dictated by the MOE, which presents an institutional pressure for advisors to work with students who may not be ready or prepared for a PhD program. As one professor from Wuhan shared:

> *A big problem in China—[you] can't kick graduate students out if they're not meeting standards. I think this is a societal problem—we treat students like kids [or] children [and] not like the adults that they are. There are no consequences for their actions—the school wants to protect them from themselves and don't want bad publicity. If they harm themselves, their advisors and the university are responsible. China's society view these students as children….*

More seriously, seven interviewees worried that any direct intervention or effort to advise a student in the graduate research realm could potential result in self-harm inflicted by the

student. Interviewees who shared on this topic believed the pressure to graduate successfully is a major reason why some students threaten to commit suicide. One professor from Beijing put it plainly:

> *I know personally professors who actually do the work for their graduate students because the graduate student is such a bad fit – they do it just so the student can graduate and get out of the lab. Professors and the university administration are afraid that students will commit suicide or do something really harmful to themselves, [and] then they would be responsible. So we spend a lot of time thinking about which students would be a good fit and won't be harmful to themselves or others. Every professor probably goes through this at some point. It's rare but if you meet a student like this, it's a nightmare. This happens everywhere.*

Other Challenges in the Graduate Research Environment

Interviewees also shared an interesting "push-pull" effect when it came to advising students on certain research trajectories. On the one hand, 11 interviewees commented on the process by which students obtain their research topics, sharing that often students are "pulled" into topics that are in line with their advisor's lab. On the other hand, five interviewees noted a lack of trained lab technicians and argued that too often students are "pushed" into activities and research that ordinarily would be done by a technician because their advisor cannot hire actual staff. As one professor from Beijing shared:

> *Professors want students to be more like technicians. Overall, there's not enough funding to hire staff or technicians so graduate students end up taking on these roles.*

Two interviewees also discussed a lack of collaboration among colleagues in China. The concern is that if advisors are not seeking each other out, then students may simply learn the poor habits of their advisors while stunting their own scientific growth. One interviewee noted graduate students outside China are often mentored by a team of scientists and not just their assigned advisor, which affords them exposure to research outside their expertise as well as opportunities to work and communicate with scientists across disciplines.

Faculty Evaluation System

Interviewees noted that the evaluation system substantially hindered China's research ecosystem and was the cause of much stress for faculty researchers. Specifically, individuals stated that most faculty researchers in China are hired on a 3-year contract and must meet certain requirements on an annual basis or over the course of the contract for renewal to be considered. Specific evaluation requirements differed by department, university, and individual academic rank but primarily consisted of publishing, teaching, and funding requirements. Twenty-two interviewees noted they had some type of publication requirement as part of their evaluation, ranging from at least two SCI publications every 3 years to three SCI publications per year. Fourteen interviewees indicated they had a minimum teaching requirement ranging from at least one undergraduate class per academic year to 270 credit hours per academic year. Fifteen interviewees stated they needed to receive a minimum amount of funding to meet their contractual requirement, ranging from 250,000 RMB per year for associate professors to 1.6 million RMB per year for professors.

Impact on Pay

Interviewees noted that one reason why the evaluation system is so stressful is because the ability to meet evaluation requirements is directly linked to their pay and potential for getting

promoted. Three interviewees explained that faculty researchers at Chinese institutions of higher education receive a baseline salary based on their academic ranks, which is then supplemented by bonuses or rewards based on their ability to meet annual requirements. Seven interviewees stated that the amount they made changed year to year based on whether they met all of their annual requirements and received their bonus. As one professor in Guangzhou explained:

> *We have 3-year evaluation systems [based on the] number of courses you taught, funding received, publications, number of mentored graduate students, etc.: [the department] give[s] you a point for every one of these requirements. This point system causes a lot of strife among professors because some teach more, some do more research more and [people] feel it's unfair. Basic salary is only 6,000–7,000 RMB per month, everything else is based on these points [and] evaluation systems.*
>
> *This evaluation system is very unfair. If you don't get these points, then your [pay] decreases. On average, an associate professor can make 180,000–200,000 RMB per year before taxes, approximately 100,000–130,000 RMB per year after taxes. On average, professors make about 230,000 RMB per year before taxes. For Guangzhou, for associate professors, if you don't take [into consideration] housing prices, then this salary is actually quite good. Guangzhou housing prices [are] the lowest of Beijing, Shanghai, and Guangzhou. But the problem is that your salary isn't steady. If you have a lot of publications one year, you may make a lot of money but next year maybe your salary decreases by a lot. You get different points depending on which journal your publication is published in, [you receive] more points for higher [impact] journals, less points for lower ranked journals.*

The instability of one's income was echoed by an associate professor from Shanghai:

I need to get 900,000 RMB per year of funding. For every 100,000 RMB that I don't get, I lose 5,000 RMB of my [bonus]. [I also need] 6 credits of teaching per semester, and graduate 8 Master's students per year. For every additional student I graduate, I get 2,000 RMB; for every one that I don't graduate, then [the university] take[s] away 2,000 RMB. There's no way I can reach 900,000 RMB in funding, so that's why my salary is actually decreasing. For professors, they need to pull in 1,600,000 RMB; lecturers or assistant professors need to get 600,000 RMB in funding. So our pressure is really high.

Interviewees also expressed concern regarding the low salaries relative to the cost of living for university faculty researchers in China. On average, interviewees stated that associate and professors take home approximately 100,000 RMB per year and 200,000 RMB per year, respectively, after taxes. Several pointed out that Thousand Talent Program recipients often make much more than faculty researchers who are domestically trained—and there are always exceptional researchers who can make over a million RMB per year, but those are rare. A professor in Wuhan explained that while his salary is considered good in a second-tier city like Wuhan, it would not be considered good for someone living in a first-tier city such as Beijing or Shanghai because of the high cost of living—particularly as it relates to housing prices and raising children—associated with those cities. As a result, interviewees noted that PhD graduates are choosing to go into industry instead of staying in academia because they can, depending on their discipline and employer, make 200,000 RMB or more per year.

Negative Consequences to China's Research Ecosystem

Interviewees noted several detrimental consequences to China's overall higher education research ecosystem as a result of the annual evaluation requirements. These include promoting

an environment that celebrates instant success—focusing instead on short-term rather than long-term research, and hindering collaborations. Specifically, interviewees voiced concerns that researchers are forced to engage in short-term research to meet their publication requirements and as a result, China as a country suffers from a dearth of long-term research. As one associate professor from Shanghai stated:

> *If [university departments] want people to meet [their] annual requirements, they'll have to keep publishing short-term research because they have to meet the requirements. I can't pursue long-term research because I need to have a job and I have a publication count requirement. I think what we need is a more relaxed research ecosystem, more freedom. We are self-motivated but the current system does not allow for self-motivation, it's too much requirement.*

In addition, because promotions are often given out based on the number of publications one has and the amount of funding one receives, interviewees described the evaluation system as a positive feedback loop in which researchers who are successful at short-term research are rewarded by titles and awards, which then furthers their likelihood of receiving funding. The concern regarding this positive feedback loop is that researchers are rewarded based on the quantity of research they produce and not on the quality or impact of their research, which can take longer to realize. As an associate professor in Guangzhou elaborated:

> *[W]hile the central government supports basic research, there are many researchers who seek funding but have ulterior goals [in that] they are not really interested in doing basic research. It is a systemic problem because we have regular researchers who publish [and] the government rewards them with titles and benefits so people do research because they want the titles and promotions. This is a historical cultural*

aspect that will be hard to change. Those who get titles rise up on positions of power and then reproduce the cycle that put them in power.

Lastly, meeting one's publication requirement is often difficult because not all publications count towards one's evaluation requirements. Interviewees explained that only articles published in English language SCI journals in which the researcher is the first or contact author count towards meeting one's publication requirements. As a result, collaborations are hindered because research faculty have to consider whether an article resulting from a collaboration will go towards meeting their own publication requirement. A professor in Beijing commented that

[e]verybody fights and competes…[b]ut in China, unless you're a first author, it doesn't count as your publication so you compete with your collaborators for who is first author, who is corresponding author, and it makes for bad relationships between collaborators.

Discussion

As shown by our interviews, there are many challenges facing China's academic STEM research ecosystem. China is not unique in many of the challenges it faces; our aim is to provide a cultural context to understand these challenges. We discuss the potential impacts that the central government, K-12/undergraduate education, graduate education, and evaluation system have on China's academic STEM research ecosystem below and discuss how this may affect China's S&T future.

Role of the Central Government

Interviewees noted both negative and positive aspects of contentious MOE policies, providing a fuller picture of government intervention and how it may remain essential to China's

research ecosystem. A primary complaint focused on the lack of transparency is how the MOE determines graduate student quota and that such a policy benefits neither professors nor students. We believe that while this may be a detriment to both professors and students, an unexpected upside, for the country however, is that the central government can easily and quickly shift the quota of undergraduate and graduate students to prioritize one discipline over another to meet shifting workforce demands. For instance, if China wants to make a big push in quantum information sciences, the MOE can dictate that more openings and spaces are available for students to major in quantum related fields and in a few years' time, the country will have approximately that number of graduates who can enter that field. The ability to quickly respond to changing workforce needs through the quota system may prove to be a big competitive advantage for China.

On the other hand, an example of how a central government policy unintentionally generated negative consequences for China's research ecosystem is the standardization and fixation on university rankings. The hierarchical system and unequal distribution of resources benefit those who rank at the top and allow certain individuals and institutions to enter elite rankings of the global research ecosystem. China experienced the largest jump in terms of higher education rankings between 2004 and 2014 with 24 additional universities entering the top 500 universities based on the Academic Rankings of World Universities while the United States had 24 fewer universities in the same list (Salmi 2016). However, many individuals, universities, and regions are left behind in this ranking system. Interviewees commented how universities, faculty, and students have become preoccupied with rankings and titles to the detriment of actual research and teacher-student relationships. Based on our interviews, rankings have become a substitute for quality of research within China and most evaluative criteria are based on scores.

Consequently, China's academic research ecosystem has become ultra-competitive and less collaborative at both the institutional and individual levels, which may hinder China's progress to advance its S&T research capabilities.

K-12 and Undergraduate Education

The general education environment substantially affects the future of China's research ecosystem as it cultivates the capabilities, especially critical thinking and academic independence, of the next generation of researchers. Our interviewees focused on how the Chinese education system, predominantly from K-12, stifles students' critical thinking abilities by rewarding those who excel at test taking and rote memorization. China's research ecosystem is thus negatively affected because students have not developed sufficient skills to question or challenge the prevailing paradigm of concepts and methodologies within a scientific discipline. In addition, interviewees noted that the sudden and drastic change for students when they exit the rigid, high-pressure K-12 education system and enter the easier and more lax undergraduate education system may not only hinder students' critical thinking skills but also result in some form of intellectual stagnation. As some of our interviewees noted, almost everyone graduates from college in China. The hard part was getting into college.

Our findings echo those of previous studies that assessed the level of critical thinking among undergraduate computer science students in various countries (Hernandez 2016; Loyalka et al. 2019). In particular, a 2016 study found that Chinese freshmen in computer science and engineering programs had higher levels of critical thinking skills compared to their counterparts in the United States and Russia. However, after 2 years of college, Chinese students showed no changes in their critical thinking skills while their American and Russian counterparts made significant strides. A 2019 follow-up study found that computer science seniors (i.e., individuals

in the last year of their 4-year college study) in the United States performed almost a full standard deviation better than Chinese computer science seniors (Loyalka et al. 2019). These findings combined with our interview findings suggest that China's undergraduate environment may not be conducive to helping students develop or advance their critical thinking skills.

Graduate Education

China's post-baccalaureate education environment appears to amplify students' lack of critical thinking and independent problem solving ability, reinforcing their K-12 and undergraduate experience. This in turn negatively influences the depth of workforce development in China's S&T industries. China's reliance on standardized testing to inform which students qualify for which graduate schools and tracks of study—derided by nearly every interviewee who discussed test taking—is one area where changes to the process may result in noticeable and positive impacts on China's graduate S&T education environment. The observation that these national tests likely only identify students with proficient test-taking skills rather than provide an accurate assessment for research aptitude is not unique. For example, increasing numbers of U.S. institutions of higher education have become "test optional" in which they accept but do not require standardized tests such as the SAT or ACT (Adams 2021) for college admissions, as new studies show that such tests are not accurate predictors of educational or college success (Allensworth and Clark 2020). Similarly, there are calls to deemphasize U.S. graduate institutions' reliance on the graduate record examinations (GRE) because of general inaccuracies in determining student success (Fedynich 2017; Moneta-Koehler et al. 2017; Park et al. 2018; Peterson et al. 2018; Sealy et al. 2019) and, in particular, restricting the flow of women and minorities into STEM fields (Miller and Stassun 2014, Miller et al. 2019). While no interviewee in our study specifically commented on improving access to graduate education of

underrepresented groups, one interviewee spoke positively about an experimental admissions process at select universities (e.g., Tsinghua) that focuses on a prospective student's personal statement, transcript, and interview rather than an entrance exam, which harkens a more holistic approach (Miller and Stassun 2014; NEAGEP 2017). Providing an alternative path to graduate school, especially one that requires a prospective student to shine a light on their research passions, may also help overcome the reported levels of disinterest in S&T graduate education.

Indeed, with the seeming prevalence of noncommittal or disinterested graduate students reflected in these interviews, incorporating innovative undergraduate-to-graduate programs, such as bridge programs (Miller and Stassun 2014) with holistic admissions processes may help produce more engaged, passionate S&T researchers. While high-performing undergraduate students tend to continue their exemplary work in graduate school, a majority of the remaining "test takers" appear to focus more on fulfilling the publication graduation requirement rather than on developing the necessary skills to become successful, independent researchers. This single-mindedness likely perpetuates the stereotype that most graduate students are of "low quality," as described by our interviewees. The lack of critical and independent thinking at the K-12 and undergraduate level, as reported by our interviewees, can translate into a lack of passion for a given research topic at the graduate research level. China's graduate research ecosystem, if it is to evolve into an incubator of China's best and brightest, may be better served when its admissions processes incorporate fewer aspects from its K-12 and undergraduate entrance systems.

Graduate education in China may also suffer, in part, from an advisor's perceived inability to objectively mentor their students due, in part, to the potential susceptibility of students negatively internalizing criticism, however constructive. While it appears plagiarism

plagues graduate students in both China and the United States (Leonard et al. 2015), the larger issue would be the suggested prevalence of mental health challenges on Chinese university campuses that appear to mirror what has been observed on U.S. university campuses (Garcia-Williams et al. 2014; Kemsley 2017; Evans et al. 2018). While a number of factors may contribute toward a student's overall mental health status (e.g., Eleftheriades et al. 2020), it is not hard to imagine a student's access to adequate mental health services helps determine whether they overcome the personal crisis (Evans et al. 2018). This may be an area where China's society is making notable strides, as demonstrated by their reported openness to and efforts to address the mental stress and anxiety associated with the COVID-19 pandemic (Qiu et al. 2020; Wang and Hernández 2020; Zhou et al. 2020). As Evans et al. (2018) assert, increasing concerns over mental health illness in graduate students should prompt university administrators and policymakers to develop and implement effective intervention strategies.

Faculty Evaluation System

The pressure to publish, as noted by our interviewees, is the same as that faced by faculty researchers all around the world (Miller et al. 2011; van Dalen and Henkens 2012; Haven et al. 2019). The perils of the publish or perish evaluation system may be exacerbated for Chinese STEM researchers because most Chinese institutions of higher education employ a contract based, non-tenured academic appointment system, as shown by our interviews. While it is true that some institutions, including Tsinghua University, Peking University, Shanghai Jiaotong University, and Fudan University, have started implementing U.S.-inspired tenure systems (Gonzalez et al. 2012), most Chinese institutions of higher education are still using fixed-term contracts, like those described by our interviewees. The evaluation system for those on fixed-term contracts means that researchers endure constant pressure to publish or face possible job

termination. Our findings indicate that this results in a research culture that promotes instant success over long-term research where individuals are rewarded for engaging in short-term research that can lead to more frequent publications. As some of our interviewees noted, this has led to the large increase in publications from Chinese researchers over the past 10 to 15 years but has not resulted in the same increase in research quality. The dearth of long-term, basic research from Chinese institutions is likely to pose a challenge to China's ambitions to become a global S&T leader. Tangible benefits from basic research are hard to predict while research is in progress, can often take a long time to be realized, and may be unexpected (Gardner 2018). By disincentivizing researchers from engaging in long-term, basic research, China may continue to find itself as an S&T follower instead of becoming the leader and world-class innovator it hopes to be.

Another reason why the pressure to publish is heightened for Chinese researchers on fixed-term contracts is because their income and pay is tightly linked to their ability to meet the terms of their contracts. Income instability, as indicated by our interviewees, can lead to individuals looking for ways to supplement their income outside of their academic position, taking their time, focus, and energy away from research. China's ability to attract new talent to its research institutions and to maintain its current academic workforce may be hindered if individuals do not feel they are compensated appropriately for the work they do.

Income among research faculty appears to pose a general challenge to China's research ecosystem. As noted by our interviewees, an average annual take home income of 100,000 RMB (~$15,000 USD; conversions calculated based on a 1 USD to 6.5 RMB conversion rate) for associate professors and 200,000 RMB (~$31,000 USD) for professors is, while not low, also not very high, particularly for those living in first-tier cities like Beijing, Shanghai, and Shenzhen.

To put it in perspective, the average monthly salary for white-collar workers is 11,000 RMB in Beijing and Shanghai, and 10,000 RMB in Shenzhen (People's Daily Online 2019), which translates to an annual salary of approximately 132,000 RMB (~$20,000 USD) for Beijing and Shanghai and 121,000 RMB (~$19,000 USD) for Shenzhen. This means that associate professors make slightly below the average salary for white-collar workers in China in these cities.

While this does not pose a problem in and of itself, lower income does pose a challenge when taking into consideration the cost of living in these cities. For instance, consider the cost of purchasing an apartment in Beijing. The average cost per square meter for an apartment in Beijing was approximately 39,000 RMB ($6,000 USD) in November 2020 (CEIC 2020). The purchase price for a typical apartment with 120 square meters (~1,300 square feet) is, therefore, 4.7 million RMB (~$728,000 USD), almost 50 times the annual salary for an associate professor. Given the high cost of living in China's first-tier cities, the salary for research faculty may not be enough for individual living expenses, let alone to sustain a family.

As our interviewees noted, it is not uncommon for research faculty to consult for industry on the side to supplement their income, not for extravagant purchases but to pay for everyday things such as housing and child raising. Another consequence to having lower pay, as noted by our interviewees, is the best and brightest Chinese PhD graduates go into industry where they can make double the income or more compared to staying in academia. The combination of low pay and income instability resulting from income being directly linked to the ability to meet evaluation requirements may pose a major challenge to China's research ecosystem. If left unaddressed in the long run, the best and brightest PhD graduates may continue to pursue non-academic careers. To the extent that individuals are choosing to go into industry rather than academia, there may be a gap between the current generation and the next generation of Chinese

students and researchers, diminishing China's ability to generate world-class knowledge or conduct innovative research.

Limitations to the Study

We acknowledge that the 40 interviewees who spoke with us are a self-selected group who not only took the time to respond to our initial 2015 survey but also indicated their willingness to speak with us. Several of the interviewees noted that they chose to participate in the survey and speak with us because they believe these topics are important to China's S&T future. Furthermore, our interviewees came from the top 25 ranked universities in China and therefore, their views and experiences may not be representative of all Chinese STEM faculty researchers at Chinese institutions of higher education, particularly those at second or third-tier institutions. Similarly, our interviewees noted that because they are faculty researchers in STEM, their views and experiences are not representative of what the research ecosystem is like for the social sciences or humanities. In addition, we note that because all of our interviewees were on fixed-term contracts, we cannot speak to the differences, advantages, or drawbacks of the tenure systems implemented at Chinese institutions of higher education.

Despite these limitations, we believe that our findings are representative of the academic and STEM research ecosystems at China's top-tiered institutions. This is because not only did our interviewees come from a wide range of disciplines and departments across many universities, but they also provided similar accounts of their experiences as researchers and the perceived challenges to China's S&T future. Similarly, we believe that the findings from this study likely represent the best-case scenarios of China's academic and STEM research ecosystems as our interviewees likely have access to more and better resources than their colleagues at second and third-tier institutions.

Lastly, we acknowledge that these interviews were conducted in 2015–16 and many changes (e.g., political, international, economic) have occurred since then that might have resulted in changes to China's academic and STEM research ecosystems. To verify that our findings are still relevant and applicable to today's environment, we spoke to three professors at international universities who work extensively and often reside in China. These additional interviews suggest that while certain policies may have changed since 2015–16, true structural changes have not yet occurred.

Implications for China's S&T Future

We acknowledge that there may have been significant changes in higher education in the 4–5 years since our interviews were conducted. In particular, we are aware that in recent years China's central government has increasingly pressed for changes intended to bring curricula more in line with the Chinese Communist Party's doctrine and Xi Jinping Thought. While some degree of Party oversight has long been a feature of Chinese higher education, it has increased under Xi Jinping's leadership, beginning with "seven don't mentions" reportedly issued by the Party Central Committee in May 2013 (China Digital Space n.d.). The "seven don't mentions" were leaked on *Weibo*, then censored. They included universal values, press freedom, civil society, civic rights, historical mistakes by the Communist Party, elite cronyism, and an independent judiciary. In 2018, the MOE issued the *Guiding Opinions on Dealing with Conducts of College and University Teachers That Violate Teacher's Professional Ethics*, and in 2019 Xi Jinping called on teachers at all levels to

> *spread mainstream ideology and directly confront all kinds of wrong viewpoints and ideologies…to guide the students to be confident about socialism with Chinese characteristics…to have patriotism deeply ingrained among the students, so that they*

will voluntarily participate in…the building of a great modern socialist country and the struggle for rejuvenating the Chinese nation (quoted in Wong 2019).

Such controls are reportedly enforced by classroom surveillance systems, ranging from cameras to paid student informants (Jiang 2020). It seems that these restrictions, however, are largely exercised at second and third-tier universities, and focused on the social sciences and humanities (Cao 2020). In science and engineering, while some of the same problems of government control over research agendas remain, there has been no significant effort to enforce conformity to official ideological beliefs—as long as faculty stay focused on their research and avoid weighing in on sensitive political issues.

At the same time, the rise in Chinese nationalism, fueled in part by political and economic conflict with the United States, has had a chilling effect on international collaboration on both sides. One result has been the increased return of foreign-trained Chinese scientists and engineers, which may yield some S&T benefits for China, although loss of ties with the United States and other technologically advanced countries also removes China from frontier research areas (personal communication 2020). While this decoupling is in large part due to U.S.-imposed restrictions on Chinese scientists working in U.S. universities or with U.S. colleagues (Postiglione and Simon 2019; Silver 2020; Subbaraman 2020), it also may have generated a concern among Chinese faculty that working too closely with their U.S. counterparts may prove costly in the long run as memories of the Cultural Revolution remain strong (personal communication 2020).

The conflict with the United States has clearly highlighted China's need to develop greater self-sufficiency, particularly in such areas as semiconductors (Kharpal 2020). This, in turn, has contributed to a renewed emphasis on indigenous innovation, resulting in official S&T

policy changes that address some of the challenges we identified earlier (personal communication 2020). In February 2020, acknowledging that the strong emphasis on publications and citations was having a detrimental effect on research quality, China's MOE and Ministry of Science and Technology (MOST), with backing by the Finance Ministry (which provides national research funding), issued guidelines intended to reduce "excessive reliance" on SCI papers as central criteria for hiring, promotion, and research funding. The guidelines reflected President Xi Jinping's call for changes 2 years earlier, which he advanced at a national conference organized to implement "guidance for educational reform and development in the new era," reflecting "Xi Jinping Thought on Socialism with Chinese Characteristics" (MOE 2018). As stated in the clarifying press release issue by the MOE,

> *In recent years, related indicators such as the number of SCI papers, the number of citations, the high-cited papers, the impact factor, and the derived ESI ranking have become academic evaluations, as well as professional title evaluation, performance evaluation, talent evaluation, subject evaluation, resource allocation. The core indicators of school ranking and other aspects have led to the phenomenon of excessive pursuit of SCI papers and related indicators in the scientific research work of colleges and universities, and even the basic goal of publishing SCI papers, high impact factor papers, and highly cited papers. Technological innovation has problems such as distortion of value pursuit, exaggerated style of study, and eagerness for quick success. This is not conducive to the high-quality and connotative development of higher education, cannot meet the requirements of educational reform and development in the new era, and is not conducive to the construction of a strong education and science*

> *and technology country. There is a strong voice from all walks of life for breaking the "SCI first" of papers and optimizing the academic ecology (MOE 2020).*

The guidelines instructed educational institutions to "improve academic peer review evaluation" and cease "filling in SCI papers related indicators," focusing instead "on the innovation and significance of representative results." With regard to faculty hiring, "the school does not take the relevant indicators of SCI papers as preconditions;" nor should schools "directly link with SCI-related indicators in resource allocation," nor "publish the rankings of SCI papers related indicators and ESI indicators" or "use indicators related to SCI papers as labels for the evaluation of scientific researchers, disciplines and universities" (MOE-MOST 2020). While the directive did not discourage continued publication in leading journals such as *Science, Cell,* and *Nature*, it also called for increased publishing in Chinese-language journals, and announced that the government would create a Chinese "scientific citation index" system "with Chinese characteristics and international influence" (as quoted in Sharma 2020).

This final guideline strikes us as potentially highly significant in the long run: just as the principal language of science shifted from German to English after World War II, it may now begin to shift to Chinese (personal communication 2020), as China's research achieves parity with the United States and other countries in a growing number of fields.

In his May 2021 speech to the CAST National Congress, Xi called for greater international cooperation in science and technology:

> *It is necessary to coordinate development and security, plan and promote innovation with a global perspective, actively integrate into the global innovation network, focus on issues such as climate change and human health, and strengthen joint research and development with scientific researchers from various countries. It is necessary to*

deeply participate in the global governance of science and technology…, and let Chinese science and technology make greater contributions to the construction of a community with a shared future for mankind.

Global cooperation, if not overshadowed by U.S./China geopolitical conflict, would go far towards addressing the challenges we have identified in China's STEM higher education system. We believe it would also be of mutual benefit to the United States, and a step forward in addressing the world's shared challenges.

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14. ABSTRACT

Although China has made significant strides in science and technology over the past few decades, it faces a variety of challenges in building and cultivating a research ecosystem that fosters innovation. To better understand these challenges, we conducted interviews with 40 Chinese STEM faculty researchers across institutions of higher education in Beijing, Shanghai, Wuhan, and Guangzhou. Interviewees reported that in general there is too much top-down governmental control on China's academic environment. For students, China's college entrance exam, the gaokao, incentivizes rote memorization and test-taking at the expense of critical thinking, resulting in a loss of direction and motivation among undergraduates. These were reported to be problems that carry over into graduate school, resulting in students who may work hard and possess strong technical skills, but lack the critical thinking ability required to engage in truly creative research. At the faculty level, interviewees reported that China's evaluation system disincentivizes collaborative, innovative, and long-term research. To meet their contractual publication requirements, interviewees noted that they are often limited to performing short-term research that rewards instant success. In addition, the high cost of living in first-tier cities combined with having an income that is based on the ability to meet one's contractual terms, interviewees noted that researchers may look for ways to supplement their income outside of their academic position, taking time, focus, and energy away from research. We argue that these challenges—both systemic and within the national academic culture—may hinder China's progress to produce the kind of home-grown innovation it has long sought.

15. SUBJECT TERMS
academics; critical thinking; education reform; innovation; research and development; science and technology; science, technology, engineering, and mathematics; STEM

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