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Leapfrogs and Shortcuts

Paths to Technological Performance on US and Chinese Strategic Evolutionary Landscapes

Rachel L. Reynolds

SCHOOL OF ADVANCED AIR & SPACE STUDIES
FROM THE PAST, THE FUTURE

AIR UNIVERSITY

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Major Rachel L. Reynolds is a 2007 graduate of the US Air Force Academy, where she majored in materials science. In her career on active duty in the Air Force, she has commanded an expeditionary air control squadron in Afghanistan and led operations at the Air Force's enlisted cyber support schoolhouse. She previously completed graduate studies in ecology and evolutionary biology at the University of Colorado at Boulder and in science and technology intelligence at the National Intelligence University in Bethesda, Maryland.

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In Memoriam

Dr. Gregory F. Intoccia, Lt Col, USAF, Retired

Abstract

This study adapts a model from evolutionary biology—the evolutionary fitness landscape—and applies it to the problem of illegal technology transfer. The author conceptualizes the strategy of technology theft as a combination of inputs that, like biological traits, result in a particular level of performance, which can equate to biological fitness. As in evolutionary biology, these input combinations are charted similarly to a topographical map to show where peaks of performance exist. The author examines three cases of illegal technology transfer by China of US militarily critical technologies from the 1980s through the early 2010s. For each case, the author inventories and categorizes the cost of the transfer to China in resources, skill, and risk. These categories then represent the x- and y-axes of the evolutionary landscape. The author further assesses China's ability to attain the US technology performance level, which is charted as the z-axis of the evolutionary landscape. The study concludes that when conducting illegal technology transfers, China trades inputs of time and money for increased risk; however, no amount of risk input enables China to attain the same level of performance as the natively developed American technology. Furthermore, this study concludes that visualizing the technology development competition between the United States and China enables strategists and decision makers to more effectively conceptualize "offensive," "defensive," and "mutualistic" technology transfer strategies. The author suggests two branches of future study: (1) fine-tuning the model with computational methods and a large-n study and (2) using the model holistically to analyze additional critical cases of technology transfer.

Introduction

The reason most people do not recognize an opportunity when they meet it is because it usually goes around wearing overalls and looking like Hard Work.

"Pickups," Logansport, *Indiana Pharos-Tribune*, 18 May 1921

Research Question

The United States' technology development strategy is a system that can be mapped to an *evolutionary landscape*—a theoretical construct to describe the performance of complex systems based on inputs and interactions, originating from the field of evolutionary biology and since adapted by a myriad of social science studies. This evolutionary landscape framework helps conceptualize constraints on the routes to peak system performance (called *available paths*). Evolutionary landscapes are much like topographical maps where high points of elevation represent high fitness or performance in an environment. The mathematical function that describes the surface of the landscape represents all the possible combinations of inputs or traits that result in a given level of fitness or performance. In any environment, a system can only opt to follow the terrain described by the evolutionary landscape's surface—that is, a system must follow *available paths* to performance. In technology development, inputs such as amount of money, time, or personnel resources spent result in a particular level of technological performance.

Other countries, especially China, engage in theft of militarily critical technologies, a phenomenon termed *technology transfer*. Notionally, their achievement of higher performance (or *fitness peaks*) through theft represents a contradiction of path availability in an evolutionary landscape. A contradiction in this sense means not following the contours of the landscape's surface terrain upon which a route from one point to another is "available." Such a contradictory path can be thought of as "leapfrogging" or "shortcutting" from a relatively low performance peak to a relatively high one via a route that does not follow the landscape's topology.

This paper examines alternate paths to the acquisition of militarily critical technology and addresses the problem of whether the theft of such technology represents a viable path to strategic advantage. I approach this problem through the lens of evolutionary landscapes applied to cases of illegal Chinese technology transfer from the past 30 years. More specifically, the paper seeks to answer the following question: How does Chinese technology transfer deviate from the evolutionary landscape paths traversed by US technology development?

Ultimately, this paper speaks to how nations build capacity for war; it considers strategic tradeoffs the US and its adversaries make to achieve domain superiority.[1] While the development and security of militarily critical technologies are in and of themselves of strategic importance, I believe the element of this paper that is of greatest strategic relevance is the conceptualization of *what it takes to achieve performance*. Understanding the different paths we and our adversaries take to maintain a technological advantage is central to properly assessing and successfully opposing near-peer competitors.

Background and Significance

The United States operates under long-standing paradigms about technology development. It relies on values and mindsets many consider the fabric of the American way of life: hard work, personal investment, and playing by the rules. This certainly is not the only way of doing things—some of the US's competitors, such as China and Russia, take approaches that rely instead on rule breaking or rule bending. Assuming that the US's methodology has, in fact, placed it ahead of its competitors in technological development (although the United States enjoys an empirically demonstrable lead in areas like aviation and naval technologies, this advantage is neither *necessarily nor solely* due to US technology development regimes), will that method enable us to maintain our advantage? What if we reevaluated the paradigms that drive technological development in the United States today—what might we gain? What might we lose? A number of key ideas from evolutionary biology can help us think outside the proverbial box of existing paradigms and expose some potential challenges and advantages of a different approach.

Background

Evolutionary landscapes. The field of evolutionary biology offers excellent models for competitive environments. Evolutionary landscapes (or adaptive fitness landscapes) are conceptual tools that enable biologists to visualize how organisms achieve higher or lower fitness relative to their competitors. Landscape thinking abstracts the combinations of traits that lead to fitness and places them on a topographic map. If the United States were to map its trek toward peak technological development performance, what terrain would it cover? How does a competitor like China visualize its peaks and valleys?

Whether taken metaphorically or empirically, as a mathematical model, landscape thinking enables a robust comparison of competing strategies.

Technology transfer. At the National Intelligence University in Bethesda, Maryland, where members of the intelligence community (IC) study science and technology and strategic intelligence, Dr. Peter Leitner teaches a course on technology transfer. A former senior strategic trade advisor for the Defense Department, Leitner has written and published extensively on the topic and was a frequent witness at congressional hearings on technology transfer and dual-use technologies throughout the 1990s. "Technology transfer," as he and other national security experts use the term (and as I intend it here), refers to the illegal movement of militarily critical technologies from the United States to adversarial or otherwise competitive nations (a more precise definition is provided later in this section). What technology transfer represents in a national security sense is the narrowing of the gap between US capabilities and those of other nations.

The difference between adversaries' advancement due to their own research and design (R&D) versus that due to technology transfer, as national security experts see it, is that in the former case, the adversary bears the cost of their own improvement; in the latter case, the US unwittingly "pays for" the technological development of its adversaries. That is, the costs of R&D, raw materials, education, manufacturing processes, and so forth are paid by the United States during development, and through technology transfer, adversarial nations illegally obtain the benefit of the US "hard work" without having traveled the hard work path themselves.

A puzzle. Thinking of technology transfer within the context of evolutionary landscapes presents a puzzle.

1. If evolutionary landscapes map a combination of factors and interactions to produce a given fitness (performance) level,
2. if paths to fitness peaks are constrained by the available paths of the landscape's topology,
3. and if the United States has achieved its current technological performance elevation because of the combination of technology development inputs (e.g., R&D, raw materials, education, manufacturing processes, economic investment),
4. then, contradictorily, technology transfer allows foreign states/actors to reach performance peaks without traveling an available path on the technology development landscape.

Considered this way, technology transfer is a "shortcut" to a fitness peak that, in terms of the evolutionary landscape model, should not exist. This contradiction raises multiple questions.

Questions. Similar to complex adaptive thinking or systems thinking, *landscape thinking* leads scholars and strategists to novel questions about the systems they study. Applying landscape thinking to the problem of technology transfer suggests insightful questions such as:

- Does technology transfer amount to a viable alternative path on the existing landscape?
- Does technology transfer defy the US's conceptualization of its technology transfer landscape?
- Do states employing illegal technology transfer attain performance by an unforeseen combination of input factors?
- Can alternate landscapes be mapped that account for the inputs required for technology transfer?
- Does mapping "theft" by visualizing it on an evolutionary landscape enable us to target key inputs and ultimately prevent the theft?
- Does the performance obtained by "shortcutting" match the performance obtained by the "hard work" path?
- Does the "shortcutting" party have a vested interest in the performance of the "hard working" party?

The answers to these questions will not only enrich the academic understanding of technology transfer but will also inform policymakers as they seek strategic technological advantages.

Possible explanations. Some potential explanations for the apparent contradiction posed by technology transfer include the possibility that there is, indeed, a contravention of the evolutionary landscape of technology performance as the US knows it. In this explanation, the landscape modeling rules themselves must be wrong since shortcut paths are not known to exist on evolutionary landscapes. Other possible explanations solve the contradiction differently: by asserting that technology transfer represents a valid but different path to the same performance peak by traveling a separate topology than the United States followed (i.e., by using a different set of input variables than just R&D, raw materials, education, manufacturing processes, economic investment, and the like). In this explanation, some other inputs must be found to account for a topology that takes the technology transfer-dependent state to the same performance peak as the US. Finally, still another explanation is that the technology transfer recipient state does not achieve the same performance as the transfer donor. This may occur whether or not the state travels the same landscape as the US. This explanation tries to establish whether or not "leap-frogging" or "shortcutting" is as valuable as "hard work" in the development of technology.

Path to a solution. One path to solving the puzzle of technology transfer and evolutionary landscapes is to compare cases of technology development with and without technology transfer. Such a solution would begin with developing the specific evolutionary landscape of technology development for the US—one with inputs like those suggested above (R&D, raw materials, education, manufacturing processes, economic investment, and so forth) and suggested by literature about innovation and development in the United States. Next, this route would assess examples of technology transfer. Such an assessment would examine the inputs required for the transfer-dependent state to accomplish the transfer (inputs might include factors for secrecy, risk, or reverse engineering). The solution would furthermore evaluate the end product of the technology development versus the technology transfer—how successful at achieving performance was the transfer-dependent state? A comparison and synthesis of the two notional landscapes and the relative fitness the states' paths led to would enable an analysis of the relative cost and benefit to each state for having pursued their chosen strategy. This paper takes the first steps on the path to just such a solution—it assesses the inputs required for China to pursue illegal technology transfer in three cases over the last 30 years.

Significance

There are clearly unresolved questions and puzzles surrounding technology transfer, but what significance do they and the concept of evolutionary landscapes have for strategists today? I contend that this line of inquiry speaks to some of the "big questions" in strategy and is not merely a technical or narrowly specialized topic.

Strategic assessment. The challenge of strategic assessment, whether it be of wartime success or peacetime decision-making, looms large for strategists.[2] A landscape model gives strategists a way to visualize their own position on a topography that represents the culmination of the choices and histories that have led them to the present moment. Landscape thinking gives the strategist a way to assess the current capabilities or performance of the United States for a particular aim and at the same time helps strategists to develop a conceptual model of the decision space and topography surrounding them. By analogy, a topographical map gives a hiker (or a search and rescue party or an oil surveyor) a reference point for their current elevation as well as the lay of the terrain nearby and distant to them.

Decision optimization. The next step after measuring and assessing performance is to optimize it—this optimization focuses on after one of the most fundamental questions of strategy: how do we know in the moment that we are advancing toward our goal? Landscape modeling not only points the way to the next higher fitness peak but also makes clear why a decline in performance may sometimes be necessary to pursue greater performance opportunities. Consider again the analogy of the hiker: if she is at the top of an 11,000-foot mountain but can see a 14,000-footer in the distance, she must be willing to sacrifice some elevation en route to her desired summit. This method is not unlike what strategic-assessment scholars Blanken and Lepore have in mind in their writing on "slowing down to keep in the lead."[3]

Additionally, as the puzzle of technology transfer suggests, it may be that the hiker does not need to travel down in elevation to achieve the next peak at all—recall that her topology is a conceptual one, not a physical one. By considering a different set of input values, there may exist a landscape for which higher performance is attainable via a purely uphill slope that sacrifices no (or relatively little) short-term performance in pursuit of long-term advantage.

Influencing the enemy. One final way that an evolutionary landscape model benefits strategists conceptually is the ability to analyze and influence adversaries. Building and plotting an evolutionary landscape maps combinations of traits, choices, and other inputs to measures of performance. This is, in essence, a novel way to approach enemy center of gravity (COG) analysis.[4] Joint doctrine and academic studies have developed multiple methods for identifying enemy vulnerabilities.[5] An evolutionary landscape is a visual map of characteristics that correlate with performance peaks, enabling planners and strategists to determine what vulnerabilities might be most impactful when targeted. Complexity analysis is not new in military planning, but landscape thinking offers a fresh perspective and potentially a more accessible one to those without formal modeling and simulation backgrounds.[6] Scientists in the medical field already perform a sort of "COG analysis" on viruses using evolutionary landscapes—their methodology represents a conceptually new approach (if a metaphorical one) for military strategists.[7]

Designing policy. In a more policy-focused but still strategically impactful way, a study of the landscape models of technology transfers enables better policies for US exports. Mapping the process of technology transfers to a landscape can illustrate the critical conditions under which a state gains the most from a transfer. If these key conditions are known, laws and regulations can be better tailored to increase the cost of illegal technology transfers to the offending state or reduce their benefit such that they are no longer desirable. Likewise, if a landscape model of a technology transfer indicates that the receiving state is no better or worse off for having engaged in technology transfer (say for a given industry in which the performance of a "stolen" technology is much poorer than the performance of the natively developed technology), it may be more costly than it is worth for the United States to bother protecting that technology at all. This would be a radical approach to a technology export protection enterprise, which exists today almost unchanged since its inception decades ago.

Definitions, Assumptions, and Limitations

This paper's thesis considers a "theft" model of technology development anathema to the United States' current "hard work" (native development) strategy. To do so, the analysis borrows and analogizes from a foundational model in evolutionary biology. To a readership of historians, political scientists, military strategists, and international relations scholars, the terminology and approach of a life scientist may seem unorthodox and possibly daunting. In this section, I introduce some of the basic vocabulary and framing used by evolutionary biologists and technologists in whose fields this paper journeys. The next section, "Literature Review," will discuss the history of these fields and will overview the current state of research specific to technology transfer and the application of evolutionary landscape models.

Definitions

Evolutionary landscape/fitness landscape/adaptive landscape. These terms are used interchangeably in this text. In this work, "evolutionary landscape" is used in a theoretical, conceptual sense—no computational modeling is undertaken here. The next section provides a more thorough explanation of how other scientists have employed the concept of an evolutionary landscape to their own fields of interest. As a general notion, an evolutionary landscape is taken to mean a topographical map of high and low points of elevation where each point is described by its inputs (traits, characteristics—see below) that produce a given performance (fitness, capacity—see below) represented by elevation on the topography.

Technology transfer. For this paper, technology transfer is defined as state-sponsored, illicit movement of technical, militarily critical materials, processes, or knowledge from the United States to adversarial nations, in opposition to US national security goals. The multitude of other kinds of technology transfers that exist are described more fully in the next section.[8]

Outputs/performance/fitness/capacity. Used nearly interchangeably, these terms are intended to convey the result of technology development or technology transfer. They may refer to a specific piece of equipment a state possesses, an effect the state can produce with some military technology (e.g., precision bombing with an inertial guidance system), or the ability (capacity) to produce a technology due to its manufacturing processes or machinery.

Inputs/traits/characteristics. Used nearly interchangeably, these terms are intended to convey the requirements for technology development or technology transfer. They may refer to the investment of time, money, materials, human capital, or intangible values (e.g., acceptance of risk) needed to produce a technology.

Available path/"shortcuts"/"hard work path." In evolutionary landscape terms, this means that there exists a series of discrete changes in inputs that, when summed, trace a topology from one elevation point to another. If a set of inputs results in a given elevation for one actor, then those same inputs cannot result in a different elevation for another actor. A state that takes a path that *should not* be available on a given landscape is taking a "shortcut"—one of the central contradictions this paper explores. The "hard work" path follows the existing terrain (takes available paths).

Terrain/topology/"landscape." Used nearly interchangeably, in this paper, these terms refer to the resultant graphical map of inputs and performance outputs. These terms are used to describe the nature of a given evolutionary landscape (e.g., multiple peaks on the terrain, steep elevation gradient of the topology, and so forth).

Transferor (donor)/transferee (recipient). As a matter of practicality, "transferor" in this paper *always* refers to the state that developed a technology natively, and "transferee" *always* refers to the state that obtained that technology via technology transfer. It is important to note that the donor/recipient relationship may not necessarily correspond to the state that took the action to perform the technology transfer. For example, if a technology transfer occurred where a Chinese agent actively stole a blueprint of militarily critical technology from a US laboratory, China would be the transferee, the United States would be the transferor, and China would have performed the transfer (as it was their agent who took the action). In another case, if a US government contractor were to maliciously post militarily critical technical data on a Chinese online forum, China would still be the transferee (receiving the technology) and the United States would still be the transferor (state in which the technology originated); however, the United States would also be the actor who performed the transfer, in the form of the government contractor.

Assumptions

The field of technology transfer, the US system of technology development, the decision-making process by states to engage in illegal activity, and the use of evolutionary models to explain competition and performance are all inherently complex problems. Several assumptions help to simplify the work undertaken in this paper. In the final section on future research, I suggest several ways to reintroduce complexity by eliminating one or more of these assumptions. Those next steps will move forward this initial study conducted under the following assumptions.

Zero-sum game. It may be considered an underlying assumption of this kind of research on technology transfer that technology development and safekeeping is a zero-sum game, wherein the gain of a capability by one state is equivalent to the loss of that capability by another state. This is not necessarily the case. For instance, the spread of the internet from the United States to other countries did not effectively negate the United States' internet capability. If anything, the fact that more countries came online during the 1980s likely benefited the United States in a synergistic way. Even in the case of the rough nuclear parity between the United States and the Soviet Union in the 1970s, the mere attainment by the Soviets of a comparable arsenal does not account for the quality and surrounding capabilities (e.g., organization, command and control, training) of that military technology. The Analysis section of this paper assesses performance outputs (fitness peaks) of instances of Chinese technology transfer. In it, I attempt to mitigate the all-or-nothing, realist approach toward measuring states' capabilities. I do so by introducing some measures of how *effective* or *ineffective* China was at employing or integrating its newly acquired technology (see Analysis section for more detail). However, the complexity inherent in assessing performance (effectiveness, capability, capacity) necessitates some simplification. In this paper, the lack of nuance in performance assessment may suggest a zero-sum game mentality. It is my hope that with further study on this topic, this assumption can be discarded and the relative value of a technology (and, for instance, whether it confers a meaningful first-mover advantage to its holder) can be assessed.

Model transferability. This paper, at its core, assumes a level of model transferability from the evolutionary landscape's field of origin—population genetics—to its field of application—military strategy, or more specifically, technology transfer. The varying levels of adaptation of the evolutionary landscape model by social scientists in a variety of fields is discussed in greater depth in the next chapter. Researchers Marks, Gerrits, and Marx collated the numerous instances of evolutionary landscapes' use in social science and highlighted the robustness and versatility of the landscape model for use in other contexts, but they also acknowledge that making the leap to a computationally useful model can be prohibitively difficult.[9] Therefore, in many cases, the landscape model was used less as an empirical tool and more as a way to sensitize other social scientists to evolutionary concepts and landscape thinking.

Limitations

Where the assumptions of this study decrease its complexity to a manageable level, the limitations listed below scope the problem in space, time, and kind. These limitations do not exist to ignore or to dismiss the significance of other instances of technology transfer; they are simply in place to provide a clear, initial proof of concept of the landscape thinking methodology. I propose that the successful mapping and modeling of US-China technology transfer can act as a template for future studies of other instances of technology transfer.

Geographic scope. This paper is limited to instances of US-China transferor-transferee technology transfer. There are a multitude of instances of technology transfer that fall outside of this geographical categorization; however, the interest in Chinese pursuit of US technology is great currently, and examples of Chinese theft of US technology abound in open-source media. Additionally, China is today aggressively pursuing novel and nontraditional modes of technology transfer including providing venture capital to small technology firms in the United States and seeking technology data via cyberattack.[10] These modernized forays into the world of technology transfer make it all the more likely that the findings of this paper will be relevant for the foreseeable future.

Temporal scope. This paper limits itself to late-twentieth century technology transfer. This period was selected primarily because its examples are distant enough to have been cataloged and detailed in the historical record, while at the same time recent enough to incorporate technologies that are still of concern today. Technology transfer regimes of various eras would likely make for fascinating study, especially those time periods surrounding revolutions in military affairs.[11] Furthermore, constructing an evolutionary landscape model for unduly broad timespans may introduce other problems. The technology may be too vastly disparate to be readily compared, or the actors deciding on a technology development strategy may have changed significantly over the timespan.

Category of technology transfer. Another boundary I have placed on the technology transfers considered in this paper is that they must be illegal and must be in pursuit of militarily critical technology. These are conscious choices that specifically have to do with separating the kind of undesirable and unexpected saltations (jumps) of technology development due to illicit technology transfer from the predictable and expected saltations that result from intentional or market-driven technology transfer. The next section goes into greater detail about the specification of the phrase "illegal technology transfer" from the other senses in which it is used in academic leadership. Here it is sufficient to note that this paper considers only technologies and activities that are shielded from the effects of the free market.

Methodology

In this paper, I select three cases of military technology developed by the US that were subsequently acquired illegally by the People's Republic of China (PRC). I categorize and assess the kinds and amounts of investment made by the PRC into technology transfer, qualify how much they "saved" by stealing the technology as opposed to developing it natively, and investigate the gaps between PRC and US performance and capability after acquisition. These categorical evaluations are exemplars of technology transfer instances, and they inform an initial, notional evolutionary landscape of the PRC's military technology development.

Other Applications

Future studies on this topic may evaluate the relative cost and benefit of these and other instances of technology transfer between the United States and China or other states. Possible avenues of future research are discussed in greater detail in the Conclusion.

Technology development is not the only area of strategic interest wherein landscape thinking would benefit analysts and decision makers. Many competitive processes can be mapped to an evolutionary landscape, and, moreover, understanding the costs and benefits of "shortcutting" or "leapfrogging" in any kind of developmental process could be critical to maintaining an advantage in multiple arenas. Some examples with clear military strategy and force development implications are training pilots, improving physical fitness, gathering intelligence, and —

Literature Review

Quality is never an accident; it is always the result of high intention, sincere effort, intelligent direction, and skillful execution.

—Birmingham, Castleman & Pierce, Inc., "Quality Advertisement," *New York Times*, 10 June 1939

Technology Transfer

As defined in the Introduction, "technology transfer" in this paper refers to state-sponsored, illicit movement of technical, militarily critical materials, processes, or knowledge from the United States to adversarial nations, in opposition to US national security goals. In this section, the derivation of this paper's use of the term "technology transfer" is presented from the literature on "technology transfer" where the term is used more broadly. The literature surrounding this paper's scoped terminology helpfully illuminates the boundaries of this study and contrasts this study with others. This review also aids understanding why technology transfer in this paper cannot be studied or considered through a free-market lens.

Basics

Technology. The literature on technology transfer cites many definitions of the term "technology," with most writers accepting a definition similar to that given by the World Intellectual Property Organization: "'Technology' means systematic knowledge for the manufacture of a product, the application of a process or the rendering of a service, whether that knowledge be reflected in an invention, an industrial design, a utility model, or a new plant variety, or in technical information or skills, or in the services and assistance provided by experts for the design, installation, operation, or maintenance of an industrial plant or for the management of an industrial or commercial enterprise or its activities."[12] In most writings about technology transfer since the 1970s, this broad category of tangible and intangible elements of "technology" is broken down into subcategories with descriptors like "hardware and software," "high technology and low technology," "equipment, documents, and skills," "production-oriented and organization-oriented," and many more.[13]

This study focuses on militarily critical technologies. In the United States, "militarily critical" is more than just a generic descriptor. The Defense Threat Reduction Agency publishes and maintains the Department of Defense's (DOD)

Militarily Critical Technologies List (MCTL), formally defining and characterizing those technologies that, in the assessment of national security and technology experts, would pose a threat to the United States were an adversarial nation to acquire them. These technologies tend to be cutting-edge or "high" technologies, they tend to be related to weapons and weapons systems or to manufacturing processes specific to certain weapons systems, or they tend to be dual-use technologies. Dual-use technologies are those that can serve both nondefense, commercial purposes as well as defense-related purposes with clear ties to national security. This study acknowledges and analogically refers to instances of technology transfer that are licit and intentional, having to do with assistance to developing countries, or that serve purely economic (nondefense) purposes; however, unless otherwise explicitly stated, this paper uses "technology" primarily to refer to militarily critical technologies.

The consensus of literature on development of US national security-related technologies is that such development depends on inputs such as innovation, policy and regulatory environment, business investment, and human capital and education.[14] Furthermore, the United States' most recent Science, Technology, and Innovation Strategy document (Obama administration, 2016), following in the footsteps of the Clinton-era National security Science and Technology Strategy (1995), focuses on talent development and innovation driven by market forces.[15] Finally, US national strategy-level documents emphasize the need to maintain a competitive advantage in technology development over adversarial nations; for militarily critical technologies, this means added layers of security and secrecy to deny adversaries access to such US-developed technologies. This secrecy and withholding of technologies from the marketplace are at odds with the democratization of science and technology in an era of globalization. Much of the literature on national security technologies acknowledges the tension between the goals of innovation and secrecy/security. A common premise among such documents is that the United States currently enjoys a technological advantage over its adversaries, though newer writings recognize the narrowing of this technology gap.[16]

Transfer. "Transfer" in the context of technology transfer also has many uses. At its core, technology *transfer* simply means the transmittal or movement of technology—materials, processes, knowledge, and so forth—from one place (physical or conceptual) to another.

Before the 1970s, "transfer" in the literature might refer to vertical or horizontal transfer—that is, movement from pure to applied sciences versus movement from location to location.[17] Since the advent and rapid increase of globalization, transfer is generally taken to mean horizontal flow—the movement of technologies from one place to another.

Transfers are categorized in many ways—they can be domestic or international (the majority of literature today studies international technology transfer, and in this paper, technology transfer is only used in the international sense). Additionally, technology transfer can be intentional or unintentional (unintentional transfer is usually referred to as "technology diffusion"); it may be categorized by geography (e.g., North–North, North–South, East–West, East–South transfer); and it may be categorized by the mode, method, or channel of transfer.[18] Regarding "geographical" categorization, the descriptors North, South, East, and West are actually nongeographically specific terms used to refer respectively to technologically and industrially advanced economies (North), economically and technologically less developed countries (South), ideologically communist and like countries (East), and ideologically free-market democracies (West).[19] This fundamental, "geographic" (political, ideological) categorization of technology transfers in the literature hints at the nationally strategic nature of such transfers. Finally, transfers may be legal or illegal. The next paragraph discusses modes of legal and illegal technology transfers in greater detail; however, throughout this paper, technology transfer refers to *illegal* transfer: movements and transmissions of technology that are prohibited by US laws and regulations, whether perpetrated by US or foreign actors/agents.

Technology transfer occurs by a variety of mechanisms, many of which can be performed legally or illegally, generally depending on the technology in question (more on what makes a transfer illegal and why can be found in the next section on US Policy). Technology transfer research identifies mechanisms, such as the sale of turnkey plants; the sale of products; licensing and patenting products, materials, and processes; reverse engineering; industry meetings (seminars, colloquia, conferences); education (abroad or imported); and especially foreign direct investment (the "full or partial ownership in a foreign subsidiary by a parent firm . . . typically [providing] technology, capital, management, and marketing").[20]

Assessing the value of a technology transfer from transferor to transferee is another focus of the literature on technology transfer; however, a model that clearly demonstrates and predicts the input, output, and value of technology transfer is difficult to generate.[21] Such valuation must take into consideration not only the explicit market value of the technology but also the sunk costs of the transferor's development as well as the cost to the transferee to perform the transfer. For illicit transfer of militarily critical technologies, which are intentionally fenced off from the market, such valuation presents an even greater challenge. This paper attempts to categorize these kinds of costs and benefits of technology transfer to both transferor and transferee. The Case Studies section begins with an explanation of how such variables are operationalized.

US Policy

This section and the one that follows on US and PRC policy respectively introduce the values and policies held by each actor regarding technology transfer. The discussion on US policy here concludes with a brief overview of how the United States views technology transfer's impact on national security.

Values. The opposing values at odds in the technology transfer debate, as summarized by Lt Col Wayne Johnson, are "the perceived need to sell overseas and the need to safeguard [military] technology,"[22] that is, the market forces driving innovation, competition, and technological economic value versus the secrecy and sensitivity of maintaining a tight hold on technologies critical to national security. This tension distinguishes illegal international transfer of militarily critical technology from other forms of technology transfer. Other technology transfers exist to benefit the transferor and transferee by increasing market opportunities for technology developers (benign/beneficial international technology transfer). Some transfers exist such that one corporation can exploit trade secrets it learns from another corporation developing a competing technology (corporate espionage). Different from both of these and other forms of technology transfer is the illegal transfer of militarily critical technologies. Because of laws and regulations surrounding national defense technologies, militarily critical technology is fenced off from the open market and thus is not expected to make the kinds of leaps and jumps (saltatory development) often seen in technologies that enjoy beneficial transfer or even illicit corporate espionage.

Additionally, values that drive the development of technology in the United States and adversarial nations surface in particular ways in technology transfer. Peter Heller's premise on technology transfer and human values is that "society is not simply a product of its technology but [also the] dominant economic, social, cultural, psychological, and political forces [that] guide the direction of technological change."[23] The US holds core values about how technology is and *should be* developed—that it comes through hard work, education, and investment. This can be termed the "hard road" to success. On the other hand, adversarial countries like China are likely to hold different values about what it takes to achieve technological success. These differing values beget differing strategies for technological development and acquisition; they underlie the hypothesis of this paper that common inputs distilled from multiple instances of Chinese technology transfer represent a road map for technology development distinct from that of the United States.

Laws and regulations. As a result of the landmark Supreme Court case of *United States v. Curtiss-Wright Export Corporation* (1936), which affirmed vast plenary powers of the president regarding foreign policy, the US government has the power to control the export of militarily critical technologies in the interest of national security.[24] With *Curtiss-Wright* as their basis, numerous laws and regulations now exist to wall off critical defense technologies from the international market. These laws include various export controls such as the International Traffic in Arms Regulations, the Arms Export Control Act, various executive orders (e.g., Executive Order 13526), Department of Defense Instructions (e.g., DODI 2040.02, *International Transfers of Technology, Articles, and Services*), and National Security Decision Memoranda (e.g., NSDM 119).[25] The collective goal of each of these official directives is to prevent US producers of certain technologies from selling or otherwise transferring them to other countries. Additionally, as discussed in the section above on technology, the DOD maintains the MCTL, which is intended to guide export control officials in making decisions about what kinds of technologies may be exported to other countries. Additionally, a variety of US government programs exist for the identification and protection of critical technologies: the Militarily Critical Technologies Program, the Dual-Use Export Control System, the Arms Export Control System, the Foreign Military Sales Program, and others.[26]

These laws, regulations, programs, and systems exist to prevent or mitigate the various methods of illegal international technology transfer. Such methods include commercial sales by US corporations that break export control laws, dissemination by US parties (corporate, academic, or government) of technical reports or data, establishment of dummy corporations to contravene US laws, the acquisition by a foreign country of an interest in US industry or business for the purpose of exporting technological materials or methods, and the outright clandestine acquisition of equipment or dual-use technology.[27]

The US government has established multiple countermeasures to the various modes of illegal technology transfer. The Department of Commerce's Bureau of Industry and Security publishes training for government employees and contractors to recognize and report evidence or suspicions of illegal technology transfer, and various export control enforcement arms exist at US ports to confirm outbound cargo is in keeping with export law. Modes of technology transfer like the theft of or illegal sharing of technical data and information or embedding a foreign academic presence in a laboratory or technical academic space with access to defense technologies can be harder to discern.

National security views. Today, the United States' posture regarding militarily critical technologies is one of balancing the interests of the United States against a foreign recipient's ability to protect shared technologies to determine their potential access to that technology.[28] This means that while many technologies, such as those having to do with weapons of mass destruction, may not ever be shared with certain foreign partners, other technologies, such as embedded navigational components, sensors, or machining processes, may be shared with certain foreign partners who can effectively protect that technology from further transfer. The United States views the protection of its technological competitiveness in defense technology as a key vulnerability to adversaries like Russia and China.[29]

PRC Policy

In addition to addressing China's values and policies regarding technology transfer, this section briefly reviews instances of Chinese technology transfer; the Case Studies section analyzes additional cases in detail.

Values. Shaped by nineteenth-century imperialism and a period of national humiliation, China embarked on a massive modernization effort after World War II.[30] When it eventually adopted the "open-door policy" in 1978, which opened the country to Western technologies and influences, China could rely only on the infrastructure it had developed internally or with the assistance of the Soviets over the preceding 20 years.[31] Since then, the final two decades of the twentieth century in Chinese technology development were marked by a breakneck pace to close the gap between their economic, industrial, and military capabilities and those of the United States.

Though some contemporary scholars of Chinese technology development and technology transfer diverge on topics such as China's "1,000 grains of sand" approach to intelligence gathering, most agree that China employs nontraditional intelligence tradecraft to acquire US secrets.[32] Whether or not explicitly or literally the case, the "grains of sand"–like patience and long-term thinking of China's technology strategists certainly embodies some of the values China espouses regarding technology acquisition. China is willing to "co-opt some of the thousands of students, tourists, business travelers, trade delegations, and scientists who visit the United States every year" to bring back pieces of sensitive technological information.[33] In fact, much of China's strategy regarding technological information gathering revolves around the slow but steady accumulation of technology licenses and venture investments. Unlike the more dramatic clandestine efforts many often envision, the majority of China's inroads in US sensitive technologies have been overt—"laid out in policy documents, discussed in the media, and implemented through venues whose general features are open to inspection."[34]

Additionally, China continues to embrace and update former leader Deng Xiaoping's guidelines for foreign policy encapsulated in his "16-character" and "24-character" strategies. The more widely known of the two, Deng's 24-character strategy from the early 1990s was updated in late 2011 to convey that China will continue to maintain a low profile while actively achieving something.[35] His lesser-known 16-character "Military-Civilian Combination Policy" instructs China to pursue "military-civilian unity, peacetime-wartime unity, priority for military production, [and to] use civilian production to support the military."[36] Combined, these values embolden China's targeting of US defense technologies to leapfrog their own capabilities ahead.

Policy. China's technology transfer strategy today is part of a "multi-decade plan" to invest in critical future technologies with both commercial and military applications.[37] To enact this plan, China engages in a variety of methods of technology transfer, both licit (sometimes marginally) and illicit. In 2018, the US Trade Representative found that multiple Chinese actions were "discriminatory and [burdened] or [restricted] U.S. commerce."[38] The four actions the Trade Representative identified were:

1. China uses foreign ownership restrictions, such as joint venture requirements and foreign equity limitations, and various administrative review and licensing processes, to require or pressure technology transfer from US companies.

2. China's regime of technology regulations forces US companies seeking to license technologies to Chinese entities to do so on nonmarket-based terms that favor Chinese recipients.

3. China directs and unfairly facilitates the systematic investment in, and acquisition of, US companies and assets by Chinese companies to obtain cutting-edge technologies and intellectual property and generate the transfer of technology to Chinese companies.

4. China conducts and supports unauthorized intrusions into, and theft from, the computer networks of US companies to gain access to their sensitive commercial information and trade secrets.[39]

Illegal transfers. The examples of illegal technology transfer by China are many, three cases of which are analyzed in the Case Studies section of this paper. The academic literature on illegal transfer, however, is relatively sparse despite the fact that many cases are unclassified and detailed in popular media, court cases, and government reports. To demonstrate the breadth of Chinese illegal technology transfer, two examples are given here, which bookend the period spanning from China's adoption of the open-door policy to the present day.

The first example is that of the NORINCO CQ, a near-replica of the US-made M16 rifle, ubiquitous in the US military since Vietnam. It was, in fact, the result of Vietnam that enabled the M16 to fall into Chinese hands—after the fall of the South, North Vietnam gained access to many US weapons including the plethora of small arms left behind, intentionally or unintentionally. These weapons flowed to China, which then produced, through a state-owned manufacturer, North Industries Group Corporation Limited (NORINCO), an unlicensed facsimile named the CQ.[40] NORINCO built enough of these weapons (not for the People's Liberation Army [PLA], but for foreign sales) that they grew to have a reputation worldwide for their sturdiness and faithful copying of their American forebear. This example demonstrates that, at a time when China was just beginning to consider opening its doors to Western economic and industrial influence, it was able to capitalize on unlicensed military technology. The CQ was not specifically sought after by China, nor did China expend clandestine resources on its acquisition—it was merely through the course of history (the outcome and aftereffects of the Vietnam War) that China came into possession of the technology to be copied. Furthermore, this was certainly "low" technology—having nothing to do with advanced missile technology, guidance systems, sensors, or other weapons of mass destruction components. Nevertheless, even if not for its own military, China capitalized on the opportunity to transfer foreign technology and benefit from it—both economically and strategically as it became a patron to actors who purchased the CQ (e.g., Syrians, Iranians, the Sudanese, and the mujahideen).[41]

A more modern example that raises important points about what technology transfer looks like in the twenty-first century is the case of ATop microchips. In early 2017, a Chinese-national-bankrolled company called Avatar bought out the struggling Californian ATop Tech which had just filed for bankruptcy.[42] The chips ATop produced were advanced enough to be categorized as a militarily critical technology for their potential use in high-tech weapons systems. Despite the clear national security concerns involved, the oversight systems within the US government—including the Committee on Foreign Investment in the United States, or CFIUS—is neither vested with the authority nor allocated the resources to pursue cases of technology transfer that do not involve the outright purchase of major defense companies or equipment. Although today's critical high-technology systems often come from small (sometimes financially struggling) companies instead of large corporations, China can operate with near impunity in places like bankruptcy courts or as a cash investor in small Silicon Valley startups. This example, while not overtly illegal, still involves the transfer of technology that should have been protected by the various systems and programs envisioned by the US export control enterprise.

The cases that will be examined later in this paper cover instances of technology transfer that fall, both chronologically and conceptually, between the above two examples. They take place shortly after the end of the Cold War, and they deal with both Chinese clandestine attempts to steal technology outright as well as with US companies that knowingly made illicit sales to boost their market share of technologies that were critical to US national security.

Evolutionary Landscapes

The terms "evolutionary landscape," "fitness landscape," "adaptive landscape," "fitness surface" (and other like terms) have specific, if debated, meanings in the context of evolutionary biology; however, these differences are esoteric enough to be of little consequence for this work. In this paper, I use them interchangeably, though I rely most heavily on "evolutionary landscape" as it is commonly taken to be the broadest in its meaning and application.

Evolutionary Biology

History. In 1932, at the sixth annual meeting of the International Conference of Genetics, researcher Sewall Wright presented his novel concept of an evolutionary landscape—a new way to conceive of, visualize, and ultimately model tendencies in evolving populations.[43] Wright envisioned a topography of peaks and valleys where each high and low point represented the relative fitness of an individual organism or a population of organisms. As organisms moved horizontally on the plane, that is, as they experienced genetic variation, those variations in turn would map to a higher or lower level of fitness. Thus, it would be possible for a given combination of traits (variations) to predict not only the fitness (height on the landscape) of an organism but also to track its trajectory on the landscape toward higher fitness peaks. Though immediately eye catching, Wright's idea was not without detractors, and the more than 90 years of intervening study in evolutionary biology have developed varying takes on his model.

Basics. An evolutionary landscape consists of input variables representing the genetic variation or possible allele (gene) combinations for a population. Every unique combination of traits results in a particular fitness in a given environment Graphically, these combinations can be plotted much like a topographic map in two dimensions with contour lines symbolizing higher and lower elevations, or in three dimensions where the peaks and valleys rise and fall through the *z-axis* over an *x-y* plane.

In plainer terms, the different choices or options available to an individual endow them with better fitness (more positive in the *z*-direction, or higher in elevation) or, alternatively, poorer fitness (more negative in the *z*-direction, or lower in elevation). In some instances, an individual or population may become "stuck" or "fixed" on a peak, having risen as far in elevation as their choices (combination of traits) will allow. This may occur on a local maximum (metaphorically, on a hill that is highest within a small distance) despite the existence of a higher global maximum (metaphorically, on a taller hill that is farther away). In such a case, only a change in the combination of inputs (choices, traits) can enable the individual or population to traverse the lower-elevation valley or saddle between the two peaks.

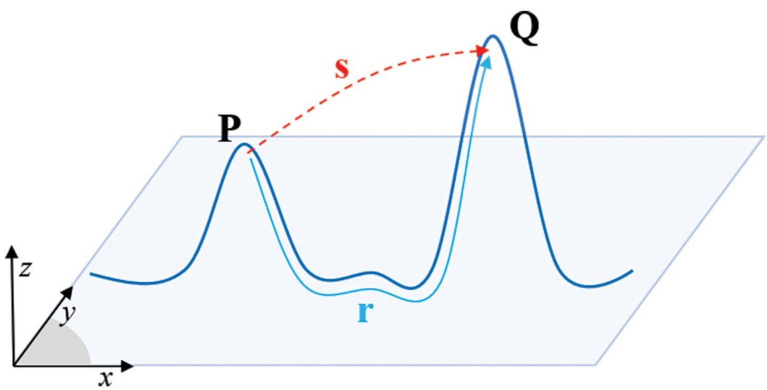

Figure 1. Exemplar evolutionary landscape
Source: Author

In figure 1, the *x*-*y* plane represents combinations of traits and choices; the *z*-axis represents resulting performance for each *x*-*y* combination. On this landscape, point P is a local maximum compared to the terrain immediately surrounding it; however, point Q is the global maximum representing the optimal combination of *x*-*y* inputs. The line "r" represents an available path from P to Q; however, traveling "r" requires a temporary loss of performance (elevation) en route to the summit Q. The dashed line "s" represents a "shortcut" from P to Q. It does not trace available sets of *x*-*y*-*z* coordinates that make up the underlying landscape and thus represents an apparent contradiction of the conceptual landscape.

One way to resolve this contradiction is to conceptualize and construct an alternate landscape (as in figure 2) consisting of different inputs which map to corresponding *x-y-z* coordinates.

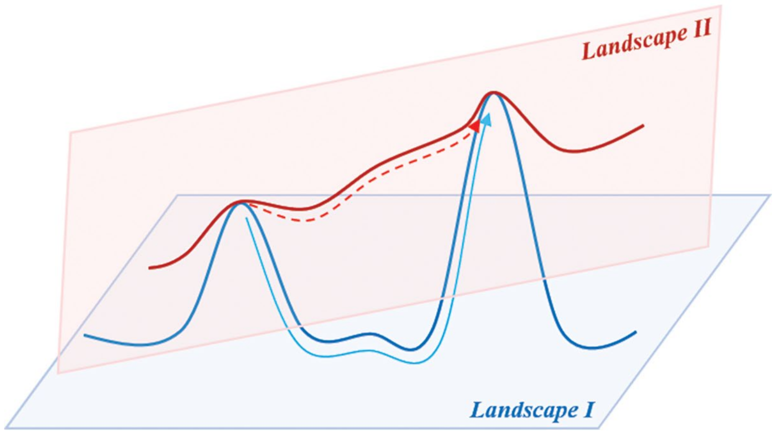

Figure 2. Alternative landscapes

Source: Author

It should be noted that path availability on natural (biological) evolutionary landscapes is limited because of the trade-off in performance (fitness) experienced due to trait exploration. This is because decreases in fitness affect survival rate. Below a certain fitness level (see figure 3), organisms will not survive and reproduce in a given environment. Thus, they may become "stuck" on a local maximum, unable to reach the global maximum without a relaxation or other change in environmental selective pressures. In the strategist's conceptual approach, a landscape may identify certain levels of performance below which the system cannot afford to perform, thus limiting exploratory *x-y* travel on their landscape. This may be true even if it means sacrificing the opportunity to reach a higher "peak in the distance."

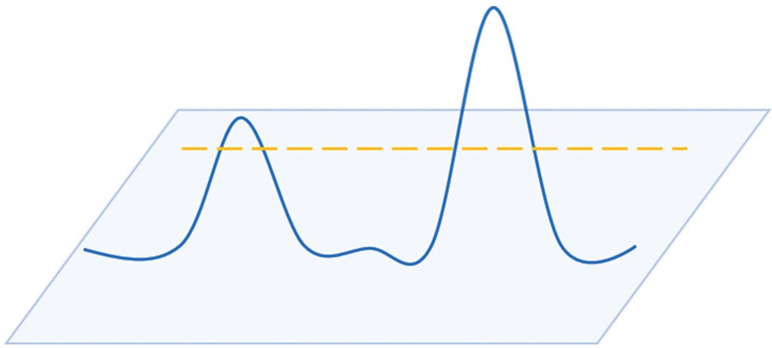

Figure 3. Minimum performance (fitness) constraint
Source: Author

Example. A charismatic example from evolutionary biology involves bird beak size and shape. Birds in many environments have adapted the size and shape of their beaks to the food resources available. This is true for Darwin's famous Galapagos finches as well as North American crossbills that are known for eating seeds from the spiny depths of pine cones. Depending on the availability of different types of pine cones, crossbills may achieve better success in their environment with specific combinations of beak size and shape. Imagine that in figure 3 the peak on the left represents a combination of shallow beak depth and average width—such a combination results in moderately high fitness for its ability to consume hemlock or fir cones (smaller and less scaled). The peak on the right represents a combination of deep beak and average width—this combination of traits allows for ready consumption of hardier ponderosa pine cones. The relatively higher peak on the right suggests the environment is denser with ponderosa pine than with hemlock and fir. Furthermore, variation in traits led to a combination of beak size and shape between the two large peaks and below the level of performance for survival. Crossbills who have such beaks will be too ill-equipped to eat either kind of cone and will thus not survive and reproduce.[44] A similar kind of analysis can be performed on complex systems beyond ecology and evolutionary biology.

Utility. Wright's first evolutionary landscape in 1932 has been "touted as one of the most famous metaphors in the history of biology."[45] It is useful as a graphical metaphor, for developing "landscape thinking" about complex problems, and as a more formal computational approach to complex evolving systems.[46] As a visualization tool, an evolutionary landscape enables researchers to view what are called "available paths" to fitness—that is, consecutive combinations of traits that lead to higher fitness peaks. Taken metaphorically, this might mean a topographical map that indicates the presence of a saddle between two peaks. Applying the concept of a landscape model to other fields of study (as will be discussed in the next section) allows researchers to hypothesize which changes of system inputs would be required to change the system performance or output to a target peak.

Social Sciences

Application to social sciences. As a "testimony to the versatility" of Wright's model, the evolutionary landscape has been adopted widely in the social sciences.[47] Dutch scholars Lasse M. Gerrits and Peter Marks conducted an exhaustive review of social science literature to survey the "diverging interpretations and uses of [evolutionary] landscapes in the social sciences."[48] They found that social scientists tended to utilize evolutionary landscapes in five general ways. Scientists tended to range from loosely adapted metaphors to modeling and simulation in the formal, mathematical language of evolutionary landscapes. Whether using landscapes as metaphors, for sense making, in modeling and simulation, for theorizing, or to map cases, social scientists from the fields of economics, anthropology, psychology, and political science found value in applying some of the foundational works on evolutionary landscapes to their work.[49]

Innovation landscapes. In addition to the social sciences mentioned in the subsection above, landscape thinking has been used to conceptualize innovation. Theoretical biologist Stuart Kauffman, one of the most influential authors on evolutionary landscapes, wrote in an article for *McKinsey Quarterly*—a business publication for senior executives—that there is a clear analogy between the evolution of species and the evolution of technologies. He argued that "this analogy can offer intriguing and fruitful insights into the ways that products, organizations, and economies develop."[50] Likewise, business consultants and innovation experts have begun to realize the benefit of evolutionary models such as evolutionary landscapes for explaining, understanding, predicting, and—most desirably—shaping growth.[51]

Military complexity. The study of complex adaptive systems has become a popular area of research among military academics, yet with the exception of a brilliantly written paper by Dr. Linda Beckerman (a Science Applications International Corporation [SAIC] think-tank guru), published online 20 years ago, the academic literature reflects no attempt to use evolutionary landscapes to describe national defense strategy topics. A few military researchers, such as Institute for Defense Analysis author Keith Green, cite instances of evolutionary landscapes for their utility as genetic search algorithms.[52] Others, like

School of Advanced Air and Space Studies scholar Eric Murphy, use the generic attribute of a "landscape" to describe agent-based simulations of advanced "prisoner's dilemma" theoretical games.[53] In these and other cases, landscapes are used merely as a reference point or subcategory under complex adaptive systems theory, but never as a tool for rigorously evaluating a real-world strategic or policy decision.

By contrast, Beckerman, in her 1999 article on the "Non-Linear Dynamics of War," uses evolutionary landscapes to explain strategic decisions made in war. She directly links the concepts of evolutionary landscape peaks and valleys to choices and inputs of historical militaries.[54] That said, military strategy is an area of study that may benefit greatly from the metaphorical, theoretical, and eventually more formal application of evolutionary landscape concepts.

Modeling

An evolutionary landscape may be represented by a metaphor, a diagram, or a model. Each applies the formal language of mathematics to the target system more rigorously. These three conceptualizations have different philosophical as well as mathematical and scientific meanings. This paper treats the evolutionary landscape of technology development as a metaphor or thought-model—and in so doing, provides the foundation for future more formal, computational modeling. Diagramming inputs of technological development for the US and for China thereby develops likely variables that can be used in a computational model.

The biological literature splits landscape models into four types: (1) a point pattern model, (2) a linear network model, (3) a patch mosaic model based on categorical patterns, and (4) a landscape gradient model.[55] Each model addresses elements of the environment and the measured population differently. Landscape gradients tend to enable comparisons between the geometry of individual fitness surfaces; they are most suited for the kinds of comparisons of interest in American versus Chinese technology development and acquisition.

Finally, modeling and simulation involves explicitly determining, defining, and operationalizing independent and dependent variables.[56] This work aims to name and suggest operationalizing methods for the evolutionary landscapes that best represent US-China technology transfer.

Case Studies

This is my body. And I can do whatever I want to it. I can push it and study it, tweak it, listen to it. Everybody wants to know what I'm on. What am I on? I'm on my bike busting my ass six hours a day. What are you on?

—Lance Armstrong, 12 years before confessing in an Oprah Winfrey interview to his part in a massive doping scheme.
Glenn Kessler, "Is Lance Armstrong the World's Biggest Liar?"
Washington Post, 18 January 2013

There are numerous instances of technology transfer from the United States to China, from ill-gotten "fiber-optic gyroscopes" to "surplus missile, aircraft, radar, and tank parts," to "radiation-hardened integrated circuits."[57] This chapter explores three such cases from three different areas of industry: nuclear weapons technology, aircraft engines, and exotic materials. Each case begins with an overview explaining the background and timeline of the scenario. Each case then concludes by breaking out what it took for China to achieve the transfer (investment), the benefit of the transfer to China (gains), and whatever China desired but was unable to obtain via the transfer (losses). In the Analysis section, I will analyze these inputs and outputs, categorizing them to build an evolutionary landscape.

Case 1: The Cox Report

In 1999, the US House of Representatives' Special Committee on US National Security and Military/Commercial Concerns with the People's Republic of China released what is now referred to as the "Cox Report," named after the committee's chairperson, Representative Christopher Cox (R-CA).[58] The report detailed several cases of Chinese technology transfer and rose to notoriety for its bold allegations of Chinese theft of nuclear weapons technology. Scholars of nuclear proliferation and arms control have since debated some of the report's findings and their meaning for US-China relations.[59] This paper considers the basic facts regarding transfer of nuclear weapons technology presented in the Cox Report and uses additional sources to ascertain China's investment, gains, and losses through the transfer.

Overview

Background. At the end of the 1976 "Cultural Revolution," the PRC began to take stock of its nuclear program, identifying its dearth of nuclear physics knowledge and poor quality of its weapons.[60] At the time, its warheads were much like those the United States made in the 1950s: "large, multi-megaton thermonuclear weapons that could only be carried on large ballistic missiles and aircraft."[61] Furthermore, the Cox Report cites the Department of Energy's generic classification of different paths for nuclear weapons development:

- The first path . . . apparently followed by the Russians, emphasizes simplicity and reliability in design.
- The second path, which the US has taken, utilizes innovative designs and lighter-weight warheads[62]

The committee assessed that China was likely to prefer US designs and that the PRC had begun, by the 1970s, to seek information from US sources on development of lightweight, mobile nuclear weapons.

By the time China signed the Comprehensive Test Ban Treaty in 1996, though, China had only succeeded at conducting 45 physical tests of its nuclear arsenal, compared to the US's 1,030 tests.[63] The PRC's relative inexperience with weapons testing, combined with the restrictions of the test ban treaty, have led to several distinct "needs" in the Chinese nuclear weapons program. These needs include "lighter and faster reentry vehicles . . . better able to stress and overcome ballistic missile defenses" and "increased warhead yield-to-weight ratio [to improve] missile ranges and accuracy."[64] The Cox Report explains how the PRC attempted to fill its knowledge and capability gaps via illegal technology transfer.

Timeline. Transfer of US nuclear weapons technology occurred over a span of nearly 30 years and was summarized by the Cox Report in 1999. The following timeline identifies the major elements and milestones of the transfers that occurred.

1970s. In the late 1970s, the PRC stole classified documents related to the US W70 neutron bomb, which it later tested in 1988. The United States had never tested a neutron bomb itself.[65]

1980s. "Lab-to-lab exchanges" were common between the United States and the PRC before they were ended in the late 1980s (they later resumed in 1993).[66] The Cox Report assessed that such visits were "[opportunities] for the PRC to collect intelligence."[67]

Early 1990s. Throughout the early 1990s (1992–1996), the PRC was rapidly testing its modern weapons in the run-up to its signing of the 1996 Comprehensive Test Ban Treaty.[68]

1995 "Walk-In." A "walk-in" in the IC refers to the unsolicited appearance of a witness at a US intelligence office, who provides information of their own accord to officers. In 1995, just such a walk-in occurred at the CIA office in Taiwan. The individual provided a classified PRC document that contained "design information on the W88 Trident D5 warhead, the most modern in the U.S. arsenal," along with other technical information.[69] It was clear from the documents that the PRC had obtained classified US technical data, despite the fact that CIA officers later learned the individual had been directed by the PRC to "walk-in" and provide the document to the CIA.[70] The Department of Energy, which had until this point suspected PRC theft of nuclear weapons information, now had its suspicions confirmed; an investigation began that resulted in the wide array of information presented in the Cox Report.

Mid-to-late 1990s. During this time, the PRC began targeting US software code that provided test data and simulation information as well as "technical information about insensitive high explosives." These explosives are "less energetic than high explosives" and thus have the "advantage . . . [for use] on mobile missiles."[71] Additionally, in March 1996, the PRC stole additional classified secrets about the US W88 neutron bomb.

Peter Lee: 1985–1997. Peter Lee was a Taiwanese American who worked alternately at Lawrence Livermore and Los Alamos National Laboratories from 1973 to 1997.[72] In 1997, in a series of interviews with the FBI, Lee admitted to "[passing] to PRC weapons scientists classified research into the detection of enemy submarines . . . [and] the illegal transfer of . . . sensitive research."[73] Beginning in 1985, through various academic lectures and presentations, Lee revealed several key scientific aspects of weapons development including:

- the physics of microwave scattering from ocean waves for use in antisubmarine warfare,
- the construction of a spherical capsule containing deuterium and tritium, surrounded by a hohlraum and heated by laser bombardment —a technique enabling the study of nuclear explosions in miniature.[74]

For his sharing of classified information, "Lee was sentenced to 12 months in a halfway house, a $20,000 fine, and 3,000 hours of community service."[75]

Epilogue. The Cox Report assessed that the PRC would likely test-fly its "next generation road-mobile, solid-propellant Intercontinental Ballistic Missile (ICBM), the DF31" by 1999, deploying it "as early as 2002."[76] In fact, the first test occurred just months after the Cox Report was published, on 2 August 1999; the second and third test flights took place in 2000.[77] The DF31 reportedly became operational in 2006, and by 2009, the US Air Force stated fewer than 15 missiles were deployed.[78] A variant called the DF31A includes a multiple independently targetable reentry vehicle (MIRV) that supposedly carries three to five warheads (all but one are believed to be decoys); the DF31AG/B includes a mobile launcher. Each has been demonstrated in military parades in 2014 and 2015.[79]

PRC Investment

The Cox Report describes the PRC's investment in this technology transfer as a "twenty-year intelligence collection effort . . . [employing] a 'mosaic' approach that capitalizes on the collection of small bits of information by a large number of individuals, which is then pieced together."[80] This "mosaic" consisted of theft of classified documents as well as meticulous research of the US academic literature, plus in-person interactions with scientists who had knowledge of the nuclear weapons research at US National Laboratories.

Some of the specific methods the PRC employed were quite simple: in some cases, they "requested reports via email from scientists at the US national weapons laboratories;" in other cases, they used "elicitation" during lab-to-lab exchange meetings, a technique that "shows familiarity with US information in an effort to 'prime the pump' to try to glean information about U.S. designs."[81] Put simply, in many instances, the Chinese simply asked for the information they wanted; what's more, they got it.

PRC Gains

The Cox Report concluded boldly that the PRC's "stolen information includes classified information on seven US thermonuclear warheads, including every currently deployed thermonuclear warhead in the US intercontinental ballistic missile arsenal."[82] This section discusses specific details about the nature of what the PRC gained operationally, developmentally, and strategically.

Operational gains. The 1988 test of the PRC's neutron bomb is one of the most apparent operational impacts of their technology transfer; furthermore, the development of modern, mobile nuclear weapons like the DF31 series of missiles shows how technical data can translate into operational reality. A caveat to this gain is that the PRC did not deploy as quickly nor as impressively as the writers of the Cox Report feared. Furthermore, suspicions that the PRC weapons are not as robust or capable as they appear (i.e., having a MIRV with multiple decoys but only one warhead) further limit the actual gains realized by technology transfer.

Developmental gains. The Cox Report's evaluation of the PRC's developmental gains includes "[saving] years of effort and resources," which would be true if the PRC had been able to advance from (in US terms) 1950s-era weapons to 1970s-era weapons in less than a decade; however, that leap is not immediately apparent from the Cox Report. The PRC also obtained "weapons design concepts, weaponization features, and warhead reentry vehicle" information that included "detailed documents and blueprints."[83] As will become even more apparent in the next case study, documents and technical data are only one piece of a very large technology development puzzle. The lack of the foundational academic know-how, maintenance data, configuration and performance parameters, and quality assurance resources may severely limit the amount of help that the PRC could obtain simply by direct theft.

A very valuable developmental gain the PRC obtained was the software code for nuclear weapons tests. Because of the ban on physical testing in 1996, the PRC sought ways to perform simulation testing of its weapons. The code it acquired through technology transfer included three specific code sequences: the MCNPT, DOT3.5, and NJOYC codes.[84] Furthermore, because the PRC has performed many fewer physical tests than have the United States and Russia, the test data they have to input into their own simulations are relatively sparse. With the three code sequences they obtained, they would be better able to determine the "survivability of systems to electronic penetration and dose penetration in humans."[85] A caveat to this gain is that it is unclear whether the code the PRC obtained included all the accompanying explanatory comments that often come with military software; without this additional content, modifying the source code for their own use would take additional developmental time and effort.

Strategic gains. Strategically, a move away from known or readily detected silo-based missiles to "smaller, modern mobile missiles" gives the PRC's nuclear enterprise greater survivability in a nuclear exchange.[86] This represents a significant achievement, even if the warheads themselves are less capable that those of the United States (or Russia). The development of MIRVs would also clearly modernize the PRC's weaponry, but it remains unclear if the technology transfer that occurred in the Cox Report truly contributed to just such a capability.

PRC Losses

The PRC still faces "considerable technical challenges" in modernizing its nuclear arsenal.[87] For instance, the Cox Report states that the PRC is unlikely to be able "to deploy an exact replica of the US W88 Trident D5 warhead," although it may have the infrastructure to make other small warheads with US information.[88] Another challenge that weapons development still poses to the PRC is "[matching] precisely the exact explosive power and other features of US weapons."[89] The Cox Report cites possible workarounds via processes from aerospace and precision-guided munitions industries; however, these are areas where the PRC also struggles (as will be discussed in greater detail in the next case study).

The National Laboratories argue that the gain to the PRC on their "investment" in lab-to-lab exchanges is mitigated by so-called "reciprocal gains." These are "[unique] insights gained" *by US scientists* during their meetings with PRC scientists.[90] While US intelligence analysts caution that such meetings are an opportunity for misinformation to be passed from the PRC to the United States, certainly the same could be said for information flowing in either direction.

Case 2: The Garrett Engine Case

Aircraft design and production is another industry where China's technological capability lags behind the US's. The PRC struggles with machining tools as well as with the baseline know-how to produce the kinds of high-performance engines required for combat aircraft. This case follows the transfer of one engine type to the PRC. In this case, the PRC may have narrowly stayed within the bounds of US law (though this fact is debatable); however, the case demonstrates the kinds of aggressive commercial tactics the PRC employed to acquire militarily critical technologies covered by export control laws.

Overview

The overview begins by contextualizing the Garrett Engine case, walks through the events, and ends with a brief assessment to demonstrate the impact this case had on US industry and policy as well as PRC strategic capability.

Background. To begin, this section first provides historical background of the case and discusses some of the technical and regulatory details to help the reader understand the terminology used throughout this case study.

History. Lacking the indigenous capability to produce high-quality, reliable military aircraft engines, the PRC established strategic goals of acquiring and developing military jet engines in the 1990s.[91] The PRC approached acquisition of this technology from foreign sources via three "tracks": diverting engines for commercial purposes to military purposes, directly purchasing engines with the desired capabilities, and creating joint ventures with foreign commercial partners to coproduce engines.[92] In the 1980s and 1990s, through both legal and illegal means, the PRC acquired multiple jet engines from foreign companies to aid in modernizing their own production capabilities. Some examples include the General Electric (GE) CFM-56 jet engine (hot sections of which are the same as those in the US F-16 fighter and B-1B bomber aircraft[93]), the GE F404 engine (identical to that found in the US F-18 fighter aircraft), the Pratt and Whitney FT8 gas turbine engine (which "represented [a] significant technical leap for [China]"), and the Williams FJ44 jet engine (derived from engines found in US Tomahawk cruise missiles).[94]

At the same time, the US foreign policy toward China in the early 1990s began to shift from its Cold War–era protectionist stance to one of greater openness in trade. This shift manifested as a relaxation in export control policies, eventually decontrolling the export of some technologies previously protected and leaving others in a policy gray zone. Much political and technical debate surrounded the details of controlling or decontrolling specific components of these borderline dual-use technologies. The next paragraphs describe the political and technical players in these debates, outline the motivations behind technology transfer by the PRC now, and provide some technical and regulatory details of the case.

Players. The primary Chinese player in this case was "CATIC," the China National Aero-Technology Import/Export Corporation. CATIC was the PRC-sponsored "corporation" organizing imports and exports of aerospace technology for China.[95] On the US corporate side was Allied Signal's Garrett Engine Division. At the end of the 1980s, *Fortune* magazine ranked Allied Signal (Allied) in the top 50 of US exporters.[96] Garrett Engine Division (GED) was at the time Allied's "largest supplier of equipment and systems for commercial transport, regional, business, general aviation, and military aircraft."[97] In the US government, the Department of Commerce (DOC) Bureau of Export Administration and the Department of Defense (DOD) Defense Technology Security Administration (DTSA) were primary players, administering dual-use export policy and providing technical review of defense-related technology transfers, respectively.[98] Finally, the Garrett Engine case spans a period of time during which the Coordinating Committee for Multilateral Export Controls (CoCom) dissolved (1994).[99] Established after the end of World War II, CoCom instituted Western bloc norms for controlling the transfer of security-related exports to Eastern bloc countries. US beliefs and assessments about which technologies should remain embargoed in the years after the fall of the Iron Curtain were mixed, as is evident in the Garrett Engine case.

Motivations. The PRC's proximate motivation was the need for a high-performance engine for its K-8 military aircraft—intended to be a trainer, fighter, or light ground attack bomber—which the PRC began developing in 1987 and later expanded to a joint project with Pakistan.[100] Multiple assessments by DTSA and the CIA concern a possible ulterior motive of the PRC: to improve development of its cruise missile engine, as minor (or no) modification of such engines could be installed in Chinese-made cruise missiles, imparting greater range and payload-carrying capabilities.[101] Ultimately, PRC leaders were motivated by their strategic desire to catch up to the West militarily, and to do so by laying the foundation to "produce advanced weapons without foreign technical assistance."[102]

Technical details. The requirements of modern, high-performance turbofan engines, such as those used in military combat aircraft and more advanced cruise missiles, are extremely strict. Minor differences in aspects like engine software and blade manufacture produce drastically different performance such that slight technical changes can delineate military from civil aircraft engine applications. Furthermore, in military aviation, "even slight deviation from optimum performance parameters can be highly problematic."[103] Several specific components of the Garrett turbofan engine are discussed in the following paragraphs to provide technical context for the chronology of the case which follows in the next section.

Turbofan engines are divided into three sections: the cold, hot, and warm sections. Air intake and compression occur in the cold section, combustion and the turbine are found in the hot section, and the warm section is composed of the exhaust nozzle where exhaust gases leave the engine. The United States was and still is the world's best in turbofan engine hot section technology, enabling US military aircraft to "outlast and outperform foreign-built military aircraft."[104] Technologies like the highly specific materials and coatings found in the hot section turbines of such engines are of special interest to China as it seeks to increase the power and durability of its engines. For these reasons, components of the hot section of turbofan engines as well as their associated manufacturing processes and software controllers are often controlled by US government regulations when engines are considered for export.

Another tightly controlled component of turbofan engines at the time of the Garrett Engine case was the "FADEC." FADECs are Full Authority Digital Engine Controls that computerize control of various engine functions in high-performance jet aircraft. FADECs rely on electrical signals and magnetos instead of mechanical linkages like throttle cables, cranks, and rods to send signals to the engine. Benefits of FADECs include reducing pilot workload, improving fuel efficiency and responsiveness, and lowering maintenance costs.[105] The advantages of FADECs make them especially useful for the "maximum propulsion performance" desired in military aircraft.[106] For these reasons, and despite the liberalization of export controls in the United States at the beginning of the 1990s, FADEC systems remained controlled under US law during the Garrett Engine case. Of note for this case is the argument between Allied Signal (alongside advocates at the DOC and certifiers at the Federal Aviation Administration [FAA]) and DTSA (alongside other technical experts at the

Naval Air Warfare Center and the Air Force Aeronautical Systems Center) over whether the Garrett engine in question used a true FADEC system or a less capable, so-called digital electronic engine controller (DEEC).

In addition to engine components, technical details surrounding the family of engines and the potential modification or diversion of engines from civil to military use also contextualize this case. The engine in question belonged to a family of similar engines produced by GED. Of note, one branch of the engine's family tree underwent "substantial improvement" with a modification dubbed "the Extended Life Turbine," or ELT. The ELT, developed by NASA, extended the engine's life by nearly 70 percent and also reduced engine noise and emissions, resulting in a stealthier infrared signature—a feature that would be especially useful in a cruise missile engine (discussed in more detail in the next paragraph).[107] In the context of the Garrett Engine case, a dispute arose over whether the engine to be exported belonged to the upgraded branch of the Garrett engine "family tree" or if it was derived from a more vanilla engine series.

Finally, the diversion of civil or commercial aircraft engines to military production lines stems from the many similarities in the engines between the two industries. As discussed above, the performance parameters of military aircraft are much more exacting than those for civil aircraft. Another way that civil engines may be used for military purposes, though, is in cruise missiles. Modern cruise missiles use turbofan engines to travel long distances, enabling their payloads to reach distant targets. In the Garrett Engine case, both the CIA and DTSA performed cursory analysis of the engine at issue to determine its suitability for adaptation in Chinese style cruise missiles. Historically, countries like Iraq, Russia, and China have modified missiles like the Silkworm, STYX, and FAW variants by either slimming down engines to fit them into the missile housing or by lengthening the body to increase fuel capacity and range.[108] Concerns about the Garrett engine's suitability for such modification arises because a technology's potential for use in cruise missiles marks it for specialized and stricter export controls.

Regulations. A wide range of international agreements, federal laws, and departmental regulations govern exports of militarily critical or national security sensitive technologies. Relevant to the Garrett Engine case are the terms "general license" or GDEST and "individual validation license" or IVL. Essentially, these two provisions allow for either more relaxed or stricter control of an exported technology (respectively). A GDEST license issued for an export means it may be sold to a foreign buyer (and resold by that foreign entity); it may also allow production processes and machinery to be sold along with the end-product technology. Conversely, an IVL is like a specific ticket for one element (or a specific quantity) of a technology to be exported at a time. Government departments may impose additional criteria on IVLs, such as prohibiting resale of the technology or its components to other countries or preventing the transfer of processes, materials, or machine tools along with the end product itself. The Garrett Engine case deals with a somewhat convoluted route of the engine through various GDEST and IVL approvals (and disapprovals) within the US Government.

Timeline and Outcome

Late 1980s–1990. Beginning in 1986, the PRC and GED began discussions about the sale of GED's engine model TFE7312A2A. A spokesperson for Allied Signal said the "2A" was representative of "early 1970s technology."[109] By 1989, Garrett had agreed to sell 30 engines to the PRC with 1,500 more engines expected to sell in later years (this number is disputed by Allied); the FAA had certified the 2A as a civil aircraft without a FADEC, and DOC had issued an IVL export license.[110] The IVL for the 2A allowed for export of three demonstration engines and one K-8 mockup for the PRC to sell to Pakistan. Because of design and manufacturing data commonalities between the 2A and other TFE-series combat aircraft engines, the 2A's IVL specified that no engine design, manufacturing, or technical data be provided to the PRC.[111] A year later (May 1990), Allied requested DOC approval for the sale of 15 more 2As to the PRC.

1991. In June of 1991, DOC approved another IVL for the 15 additional engines, adding a DOD stipulation that prevented the transfer of "design methodology, hot section repair/overhaul procedures, and manufacturing information."[112] In the fall of 1991, due to relaxations in CoCom guidance, engines with DEECs were decontrolled, while engines with FADEC systems remained controlled. This change apparently made the 2A decontrolled, as Allied maintained that it was only equipped with a DEEC system. If true, the 2A would no longer require IVLs and could instead be exported more freely under a general license (GDEST). By November, the DOC informed Allied of the relaxation in regulations such that the 2A was decontrolled in its entirety (not to include production technology).[113]

In December, Allied significantly improved the 2A engine by installing an "Extended Life Turbine" (ELT) modification. This upgrade enhanced the damage tolerance and life expectancy of the engine, making it "more durable, reliable, and generally more appropriate for use on military aircraft. No applications of this engine to civil airframes are known . . . only military."[114] What made this upgrade even more impactful was information that came to light during DTSA's 1992 technical review of the Garrett Engine case. DTSA found that the 2A engine was not, as Allied claimed, derived from the TFE7312 ("2") series of engines but rather from the TFE7313 ("3") series, which was "beefed up . . . to meet [the needs] of increased throttle excursions and operational envelope of trainer aircraft. . . . The kinds of things one would do to militarize an engine to meet a different duty cycle."[115]

1992. In Summer 1992, the PRC began inquiring about the possibility of coproduction of the 2A in China; during the same time, the previously ordered engines were found to be bound for the PRC complex responsible for building cruise missile engines, in apparent disregard for the DOC's "BAD END USER" criterion for missile technology controls.[116] From August through September of that year, engines began to be shipped to the PRC, while at the same time the CIA was validating the 2A as a possible engine for the Chinese Silkworm cruise missile; DTSA confirmed the CIA's analysis in late November. By December, DTSA, the Naval Air Warfare Center, and the Air Force Aeronautical Systems Center had undertaken inquiries into the digital engine controls on the 2A engine. Each confirmed that the Garrett engine was, in fact, equipped with a FADEC, stating unequivocally, "the DEEC . . . is 'Full Authority' " and "[there is] no question as to [Allied's] DEEC being a FADEC."[117]

1993–1994. Having been advised to continue submitting IVL requests until the FADEC issue was resolved, GED requested an IVL for the export of 15 more 2As for installation in K-8 trainer aircraft to sell to Bangladesh and Pakistan. Reexport to Bangladesh was approved, while reexport to Pakistan was disapproved because of missile proliferation ("BAD END USER") concerns.[118]

At the end of March 1994, DOD assessed that Allied Signal/Garrett was seeking export approval for 1,000–2,000 engines. A week later, the US government reached an interagency agreement to "carve out" the Garrett 2A engine's "DEEC" from the definition of export regulations on FADEC systems, essentially releasing the 2A from CoCom requirements and making it eligible for GDEST general export licenses.[119] Later that year, in September, CATIC preliminarily agreed to start a joint venture with a British aerospace company which would provide digital engine controls to the K-8 aircraft.[120]

Late 1990s. In early 1995, Allied applied for a license for Garrett engine production including engine components and assembly; they were limited only by the laxer provisions of GDEST license requirements. Later that year, after having already shipped approximately 40 engines to China with plans to export 18 more, Allied announced they no longer planned to coproduce engines in China, citing US government concerns about "potential misuse of transferred technology."[121]

Changes to Department of State technology controls in late 1996 turned aircraft engine hot section technology over to the Commerce Department for oversight, emphasizing potential export benefits over proliferation or security concerns. In 1997, the PRC attempted similar deals to the ones that had fallen through with Allied Signal—this time, targeting Pratt & Whitney technology to improve the range and stealth of Chinese cruise missiles. The $30 million joint venture also involved an Israeli turbine blade manufacturer and another aerospace engine developer in the PRC.[122]

Assessments and Implications

What, ultimately, did the PRC achieve from this instance of technology transfer, and what impact did the transfer have on Chinese capabilities? This section briefly assesses the Garrett Engine case before determining what the PRC's investment, gains, and losses were.

Assessment. Overall, from 1992 to 1996, the PRC physically received some 59 Garrett 2A engines. Reportedly, when coproduction plans were halted, the PRC canceled their remaining orders.[123] Some of these engines were likely reexported to Bangladesh, Pakistan, and four to five additional countries included in one of the early IVLs. The engines may have been "demonstration" models or included in Chinese K-8 trainer aircraft sold to those countries. What China did not receive was a coproduction plant with Allied in China. Additionally, CATIC received supporting documentation and data for the Garrett engine as allowed by GDEST. Despite the GDEST's laxer stipulations, there were still elements of documentation, including software source codes, certain materials and process parameters, and design analyses, that were controlled and protected from transfer.[124]

US government regulations surrounding export controls changed significantly throughout the Garrett Engine case. The variations occurred because of shifting national priorities about security and trade. Additionally, organizational politics and behaviors likely shaped interagency agreements and decisions about license approvals. While the Garrett Engine case is surely one of technology transfer, in some ways it may be viewed as a legal one, if just barely. "BAD END USER" and other concerns about the aggressiveness of both US commercial and Chinese government parties suggest their actions certainly skirted the edge of legality, if not at times straying over the boundary between licit and illicit.

Implications. China's twenty-first century "strategic imperatives" for its aerospace industry are: (1) to avoid dependence on foreign parts, (2) to mitigate Russian unwillingness to supply engines, (3) to develop autonomy in aircraft sales, and (4) to mitigate poor after-sales service by Russia.[125] Overarchingly, the PRC seeks native capability for high-volume, high-performance combat aircraft engine production, a capability for which it now relies primarily on Russia. The harm DTSA and other national security experts predicted might come from the wholesale transfer of Garrett engine technology to the PRC included advanced tactical engine performance and even cruise missile improvements, not to mention "flow-through" of sensitive technologies to other proliferant countries.[126]

As of the early 2010s, China still struggled with many of the same issues it sought to overcome via technology transfer from Allied and other foreign aerospace companies at the end of the last century. Russian engine imports still represent China's aerospace Achilles' heel, and weak points like "turbine blade production and process standardization" continue to beleaguer China's indigenous engine production.[127] Additional attempts by the PRC, before and after the Garrett Engine case, both legal and illegal, to acquire technological improvements suggest the wide net the PRC was willing to cast to "catch up" to the West.

PRC Investment

The investment China made to gain technology advancement in the Garrett Engine case stemmed from its three primary "tracks" of technology transfer: diversion from commercial uses, direct purchase, and joint venture.[128]

Diversion from commercial uses. To divert the Garrett engines from their commercial use to military application required multiple steps: send the engines to a military equipment production site, modify the engines for use in either tactical aircraft or cruise missiles, and enhance the software and engine performance parameters to meet military specifications.[129] Delivering or moving the engines to a different location than that provided for in the license agreement would be in violation of the law, and flowing the technology through to a proliferant country like Pakistan would further violate China's "pledges to the US to abide by the MCTR, an export control agreement that prohibits the transfer of supporting equipment and missiles capable of delivering 500 kilogram payloads more than 300 kilometers."[130]

Direct purchase. Direct monetary costs to PRC's CATIC included a per-engine price tag of $500,000 plus $480,000 of spare parts—and the potential value of Garrett's contract to supply K-8 jet engines totaled $2 billion.[131] Embedded in their direct purchase of Garrett engines was a requirement to reverse engineer the engine for use in cruise missiles, the potential for which was confirmed by the CIA and DTSA and the prevention of which was not a condition of Allied's export licenses.[132] Much of the "cost" of flaunting direct purchase restrictions was borne by Allied's GED, which provided inaccurate, misleading, or intentionally false documentation to the DOC and DOD evaluators in charge of administering and overseeing export licenses.

Joint venture. The PRC attempted twice to develop coproduction capabilities with Allied and was ultimately denied; however, they also worked toward joint ventures with other countries to obtain production of related technologies.[133] For instance, just one of these joint ventures with Pratt & Whitney came at a monetary cost of $30 million.

PRC Gains

Explicitly, the PRC gained the value and capability of 59 end products—Garrett 2A engines for immediate installation and use (or reexport). The Garrett engine has a "very efficient clean burning hot section," and the "design of [its] fuel injectors, cooling setup, and metal alloys would be of great value to a new military aircraft engine."[134] In particular, the 2A's fan would "provide state of the art blade design, compressor design, and alloy information."[135] DTSA considered this transfer to have "enabled the PRC to equip military combat aircraft with US civilian engines," which "constitutes providing direct support and operational improvements to the People's Liberation Army."[136]

Furthermore, DTSA also assesses that the PRC gained "profound missile [technology] . . . as the engine is a small, high thrust, ultra-low noise and ultra-low Infra-Red signature system perfectly suitable for insertion into Chinese-made cruise missiles such as the STYX and Silkworm series."[137] Without blade coating technology, PRC could still produce a turbojet (sans fan) variant as a cheap disposable engine with sufficient thrust (nearly 1,400 lbs.) to fly a Silkworm class airframe. Even without production technology, a spare TFE731 could provide enough data for reverse engineering and incorporation into Chinese small gas turbine development efforts. Additional gains associated with missile-ready technology like the 2A engine include, according to DTSA:

- Exposure to US gas turbine engine production technology and know-how
- Countless man years in development time on the WP-11 cruise missile and low-observable work
- Improved fuel efficiency/range of WP-11 powered cruise missiles
- Increased reliability, range and payload, fuel efficiency
- Indigenous production [no reliance on foreign assistance][138]

DTSA additionally stated that CATIC was "quite capable of 'repackaging' the engine to make it a smaller size without the benefit of outside assistance," and because of the much lower lifetime hours required of cruise missiles, "a great deal of 'repackaging' latitude will be available for PRC engineers."[139]

In itemizing what the PRC gained from the Garrett Engine case of technology transfer, it is also necessary to consider what it *did not spend*—cost savings by choosing a technology transfer route represent gains to the PRC. These instances of *not having had to spend* time and money on R&D are found in statements about how much the *transferor spent* to develop the technology natively. While considering the R&D costs of the United States, it is important to separate out the costs for components that are decontrolled and allowed for sale on the market versus the costs of those components the US government specifically fences off from the international market with export controls. For instance, the monetary cost alone of FADEC systems purchased by the US Air Force in the late 1980s was $7.7 million. This component (and any future potentially reverse-engineered components) would be gained by the PRC despite the FADEC's presumed embargo. The cost was borne by the United States, but the benefit went (possibly illegally) to the PRC outside the bounds of the licit free market. Likewise, the cost of development of the ELT modification to the series of engines to which the 2A belonged was borne by NASA.

PRC Losses

The failure of their desired coproduction venture represented a lack of return on the PRC's investment. DTSA estimated the potential gain of coproduction, a value that the PRC was unable to realize in the Garrett Engine case: "The PRC's military manufacturing base would benefit greatly from the more subtle transfer of technology resulting from the engineering 'hand holding' a coproduction arrangement would provide. The PRC would learn many of the critical 'black arts' involved in the design and manufacture of gas turbine engines, such as systems integration and mating multistage compressors. Such skills would allow them to solve many disabling problems currently besetting their indigenous military and civilian gas turbine engine production efforts."[140]

This assessment was echoed by *China SignPost* experts in 2011, who provided insight into the state of Chinese aircraft-engine production technology since the conclusion of the Garrett Engine case. It can be safely assumed that, had their investment in Garrett engines paid off to the extent that the PRC desired (or DTSA analysts feared), the PRC would not still be lagging in so many critical areas of aircraft engine production. Areas in which "China's ad hoc, eclectic approach to strategic technology development truly manifest themselves" include "standardization, integration . . . and quality control."[141] Would transfer of technology in the Garrett Engine Class have had an impact on these less tangible aspects of Chinese aviation prowess? According to Allied, yes.

Allied produced a briefing discussing the kinds of training that CATIC would receive if their planned coproduction venture had moved forward. Such benefits included "training in engine assembly/disassembly techniques and fabrication of assembly tooling, training in engine test procedures and setup of test cell, manufacture [of] hot section components, manufacture [of] DEEC, indigenous production of nonrestricted castings/forgings, training in repair and overhaul procedures and setup of overhaul depot, and training in manufacturing processes."[142] None of these training elements were realized with the scuttling of the coproduction venture for which the PRC had so deliberately laid the groundwork.

Other aspects of technology that the PRC *could have* improved, had their transfer been truly "successful" include "tooling, design capability, and systems operations and maintenance"—exactly the kinds of dependencies they still seek to eliminate in their production capabilities.[143]

Case 3: "Terf" Wars

The final case study in this paper deals with the exotic materials industry. China remains one of the world's greatest sources of rare-earth elements; however, it still falls behind the United States in developing these elements into useful materials. The case hints at the kind of monopolistic power China could wield over this strategic industry if it were to overtake the United States in materials development and production.

Overview

The technology transfer case of Terfenol-D has been less extensively discussed in academic, political, and military literature than have the other cases outlined here. Instead, it has primarily been covered in popular media (contemporaneous to an FBI investigation of some of the participants). While the lack of certain kinds of governmental assessments and documentation acts as a drawback in terms of the amount of detail available for the timeline, in other ways it shows that even briefly documented instances of technology transfer can provide the kinds of data needed to construct an evolutionary landscape of inputs and outputs.

Background. In 1986, Deng Xiaoping announced the "863 Program," which focused on acquiring and developing cutting-edge technologies for the PRC. Renewed in 1996 and extending through 2010, the follow-on "Super 863 Program" continued the 863's agenda, "which apparently failed to meet the Chinese Communist Party's (CCP) expectations."[144] Both the 863 and Super 863 programs explicitly listed exotic materials, such as "composites, rare-earth metals . . . for military aircraft and other weapons."[145] The Super 863 program was in effect for the duration of the Terfenol-D Case.

Terfenol-D is an exotic material originally developed by the US Navy in the 1970s.[146] Its name derives from its component rare-earth elements: **ter**bium, iron (chemical symbol **Fe**), and **d**ysprosium as well as its "birthplace" the **N**aval **O**rdnance **L**aboratory—hence, Terfenol-D. The magnetic and chemical properties of the material cause it to change shape in the presence of a magnetic field.[147] This ability makes it useful for a variety of commercial purposes as well as for specialized sensors, such as those in high-tech sonar devices found in submarines. Terfenol-D's potential military applications for subsurface warfare made it, in the early 2000s, a dual-use technology that the DOD "jealously [guarded]."[148]

Timeline and outcome. Although Terfenol-D was developed in the 1970s, it could not be manufactured affordably; for help, its Navy inventor, Arthur Clark, turned to the Department of Energy's Ames Laboratory at Iowa State University, home of the leading experts on rare-earth metals.[149] Around the year 2000, the PRC emplaced students at Ames Laboratory; the PRC students gained employment there and were able to gain access to scientists working with Terfenol-D. One later admitted to having given the information he gleaned to the PLA.[150] Although Terfenol-D material itself is tightly controlled by export regulations, "possession of . . . the material would not by itself reveal the process" used to create it; however, via academic "problem-solving discussions" at Ames Laboratory, the PRC students were able to "obtain enough information to develop a crude version" of it.[151] A Chinese company founded in 1998, Gansu Tianxing Rare Earth Functional Materials Co. Ltd. (TXRE) claimed to have developed Terfenol-D on its own.

Ames Laboratory contracted the company Etrema to work on production of Terfenol-D; Etrema was the "only US company authorized by the Navy to work with Terfenol-D."[152] In 2000, the company was hacked, most likely by the PRC.[153] As Etrema would email clients about sales of Terfenol-D, those same clients would, within hours, receive emails from TXRE, offering their own sale of Terfenol-D. While Etrema views TXRE's product as pirate, knock off, or copycat versions infringing on its patent, the US government is more concerned with the illegal transfer of the production technology and its potential for military applications.[154]

In 1999, another magnetostrictive alloy—Galfenol—was discovered by the Naval Surface Warfare Center Carderock Division's Magnetic Materials Group in partnership with Department of Energy's Ames Laboratory.[155] Galfenol represents the next generation of smart magnetic materials. In 2016, *Td*Vib LLC purchased Etrema along with the technology to produce Terfenol-D and Galfenol. The scientific literature today contains research on Galfenol published by both American and Chinese academics working together.[156]

PRC Investment

An FBI official who investigated the Etrema hacking incident summarized the basic recipe for how the PRC initially obtained controlled information on the production of Terfenol-D: "This is a classic example of how the Chinese collect dual-use military technology. . . . Students come here; they get jobs; they form companies."[157] In 2000, a little more than 50,000 Chinese nationals studied at US universities (that number for the 2018–2019 school year was over 369,000, accounting for more than 30 percent of all international students at US schools).[158] While only "a small percentage are involved in intelligence and technology-gathering work," other nontraditional collection methods, such as "husband-wife teams" and academic conferences and trade shows, are all avenues of investment for PRC technology acquisition and development.[159]

Additionally, the PRC must maintain numerous front companies (US government officials and Chinese state-sponsored news outlets differ as to the number, ranging as low as 681 to more than 3,000) as well as "a complex web of factories, institutes, and academies . . . each [having] an import/export corporation to facilitate the import of technology and knowledge."[160]

Another major investment was the effort and risk required to hack Etrema. Unclassified reports do not divulge who did the hacking or how the hack took place, but open-source media suggest that it may have only been the company's email servers that were hacked, not necessarily its file storage or technical systems.[161] In both cases, risk exists, and expertise is necessary; however, they are not equivalent.

PRC Gains

The PRC can benefit directly from its acquisition of Terfenol-D in several ways, for example improved military capabilities and strategic monopoly of rare materials. Terfenol-D, in addition to its applicability to high-tech sonar devices, "also has applications for advanced aircraft and spacecraft," such as "a multiple-warhead missile stage and . . . 'smart' aircraft wings."[162] The TXRE website lists several Terfenol-D applications it is researching: military underwater sonar, marine engineering, ultra-precision machine tools, fuel injection valves, and aircraft wing control.[163] Each of these applications is a specific area where China lags the United States in technology development and is a category of controlled exports in the United States.

China is one of the world's leading raw material resources for rare-earth elements. Specifically, the terbium and dysprosium found in Terfenol-D "are most commonly found in the Boutou region of northern China."[164] Even if China is unable to exert a strategic monopoly over these elements, the very presence of "pirated versions" of materials like Terfenol-D may "[harm] the metal's still-fragile reputation," causing military end users in the United States to distrust it and miss an opportunity for an important military application.[165]

As discussed in previous cases, *costs of development to the United States are, in effect, gains of technology transfer for the PRC.* The US Navy spent millions on the original creation of Terfenol-D, and it took private contractor Etrema more than a dozen to successfully produce the material affordably.[166] These costs were, at least in part, bypassed by the PRC by emplacing students in universities to gather information the PRC either could not or chose not to develop natively.

PRC Losses

Two key points characterize what the PRC "lost" in its attempted technology transfer of Terfenol-D. One is that the version of the material they were ultimately able to produce was only a "crude version," inferior, in the estimation its US creators, to the product made by Etrema.[167] The second point is that the PRC has not, presumably, created a commercially successful version of Terfenol-D's successor, Galfenol. Whereas TXRE immediately began to poach clients from its competition via email hacking, no such report exists for Galfenol and *Td*Vib, nor does the TXRE market Galfenol. The material is apparently still under academic research in China, presumably with the help of researchers like those at Ohio State University who collaborate with PRC students on Galfenol projects.

Analysis

Always presume that the enemy has dangerous designs and always be forehanded with the remedy. But do not let these calculations make you timid.

—Frederick the Great, Instructions for His Generals, trans. Thomas R. Phillips (Harrisburg, PA: The Military Service Publishing Company, 1944)

Evolutionary Landscape Building

To construct an evolutionary landscape by examining cases of a strategy-like technology development requires a certain level of abstraction. In this analysis, some individual traits will be combined to reduce the number of dimensions in the landscape visualization. In future computational studies, such simplifications should be less necessary, as long as enough computing power is available to consider the number of factors involved.

In this analysis, the Case Studies are broken into their component "inputs" and performance "outputs." Inputs are those things that were required for each instance of technology transfer to take place. Performance is the benefit (or lack thereof) obtained by the transferee from the transfer. These inputs and performance outputs are given a score that rates them "low," "medium," or "high." To increase the computational complexity, in the future, each of these scores should increase in granularity (for example, scoring on a scale of 1 to 10).

Biologically speaking, each input is like a trait (e.g., eye color) and each score is like an alternative form of that trait (e.g., blue, green, brown). An even more specific genetic analogy would say the categories can be thought of as genes and the scores thought of as alleles (one or more alternative forms of the gene). Biologists have a variety of methods to ascribe quantitative fitness scores to organisms' or populations' genetic makeup; this paper produces two simple visualizations of an evolutionary landscape model for technology transfer. These are not the only ways to visualize the landscapes; however, they are the most common in the social sciences.

Inputs

In each of the three cases of technology transfer (outlined in the Case Studies), several main categories of inputs stood out. For each case, the time (duration) it took to complete the transfer was a factor, as was the amount of money required to produce the transfer. In this analysis, time and money are grouped into an input category called "resources." Another kind of input for each transfer involved expertise or effort. These are slightly different in that expertise implies a level of training, knowledge, education, or practice; effort implies difficulty or hard work over time. Because time is already considered an input under the heading of "resources," the kind of effort represented by patience or hard work over time is, in a way, already accounted for by the "resources" category of inputs. For this analysis, then, the second main category of input is termed "skill," denoting the level of difficulty or specific knowledge required to perform the technology transfer tasks. Finally, the element of risk was present and very apparent in every case. This risk manifested primarily in the illegality of the transfer. The transfer's legal consequences, such as potential jail time or fines as well as the political fallout of violating treaty requirements, are encompassed in this third category called "risk." The technology transfer inputs are categorized as:

- Resources: time and money
- Skill: expense and effort
- Risk: legal and political consequences.

Scoring Inputs

In each case study, the inputs that comprised resources, skill, and risk were different in the degree to which each transfer relied more heavily on one or the other trait. For instance, the Cox Report case of nuclear-weapons information theft represented a much higher degree of risk than did students asking academic questions about TerfenolD. Thus, cases of technology transfer may score relatively high or low in each category.

For this analysis, each input or trait is given a score of low, medium, or high within the context of the case in spite of their absolute comparison between cases. For instance, if the technology transfer of a new military uniform design cost $10 million (which might be considered a high cost for that kind of technology) while the transfer of a new kind of satellite for orbital warfare cost $50 million (which might be considered a very low cost for such technology), the uniform design transfer will score high and the satellite will score low for monetary input even though in absolute dollars the satellite cost more.

Finally, each input is scored with consideration for the extent to which that input directly related to the *transfer* of the technology, not the technology's native development costs. For example, if a Chinese engineer stole the blueprints for a new aircraft component, the cost would only be the time it took for her or him to accomplish the theft, the risk associated with that theft, and the tradecraft needed to perform the theft. In this example, the underlying cost of maintaining an aircraft production and manufacturing site is not part of the technology transfer score because that site is considered part of the native development cost, not the cost of the transfer itself.

Table 2 (below) shows the classifications of the three cases' inputs and summarizes their scores.

Cox Report. The Cox Report was a case where the PRC took huge risks to obtain performance but put in relatively little skill and only a moderate amount of resources.

Resources. The transfer of nuclear weapons program information detailed in the Cox Report cost the PRC almost nothing but time. Over 20 years of collection using a "mosaic" approach, the PRC pieced together bits of information to move their weapons program forward; they spent relatively little money on direct acquisition in this transfer.[168] There may have been small academic conference fees or travel fees, but the Cox Report cites no major expenditures to acquire the information they sought. For this reason, the money trait scores low while the time trait scores high.

Skill. The skill required solely for the technology transfer described in the Cox Report was low. In many instances, PRC operatives simply asked for the information they desired, whether at academic conferences or via email. Although the technique of elicitation suggests some tradecraft, it was not the kind of expertise that took years of academic education. Furthermore, although part of the effort involved in this transfer required a great deal of patience, the time component of effort is already accounted for by the time trait in the resources category.[169] Thus, both elements of the skill category scored low.

Risk. The legal and political risks associated with the Cox Report transfer were extremely high. The political interest in nuclear weapons and proliferation in the Cold War was high, and the personal legal risk undertaken by those who engaged in criminal activity to further the technology transfer of nuclear weapons information (like Peter Lee) was high. Peter Lee, one of the key technology transfer agents, lost his job and security clearance, received a 12-month sentence with a high fine, and suffered other personal consequences.

Garrett Engines. In the Garrett Engines case, the PRC required a moderate amount of resources and skill but also exposed itself to high risk to obtain a moderate performance payoff.

Resources. The resources spent on the Garrett Engines case were weighted more heavily toward money than time. This was a case of foreign direct investment and joint venture more so than it was a case of long-term spying or information gathering. The transfer case spanned several years, but the PRC began obtaining value (engines) relatively quickly and continued to make purchases and acquire engines throughout the longer-term joint venture attempt. Monetarily, the investment was high within the context of the case. At "$500,000 per engine plus $480,000 in spare parts" for 59 engines, the direct investment added up to tens of millions of dollars, at least.[170] The PRC paid the market price for engines despite the fact that those engines should not have legally been part of the market (they were intended, in the assessment of some, to have been fenced off from the free market by export controls). Inputs in the resources category thus rate a low score for time and a high score for money.

Skill. The skill required for the Garrett Engines technology transfer was moderate in that, to complete the transfer and realize the military value of the dual-use engine technology, the PRC would have to modify its existing cruise missiles or incorporate the hot section of the engine into its tactical aircraft. While certainly possible, as the CIA assessed, these modifications required some additional expertise and effort. It is notable, though, that in evaluations in the early 2010s, authors assessed that the PRC still lacked some of the baseline expertise for high-performance aircraft engine production.[171] Accomplishing the technology transfer itself took almost no effort nor any specialized tradecraft on the part of the PRC—it merely benefited from changing laws, loopholes, and legal gray areas surrounding export controls of dual-use aircraft engines. For these reasons, the expertise trait scores medium and effort scores low.

Risk. Although the PRC mitigated some of the risk of its investment by putting its business partner, AlliedSignal, in the precarious position of being on the wrong side of export control law, it still exposed itself to high risk in multiple ways. First, diverting purchased engines to an alternate (military) location violated laws and purchase agreements. Second, the PRC violated treaty requirements by passing engine technology along to Pakistan. In both instances, the legal and political risks were high.

TerfenolD. In the last case of TerfenolD transfer, a low-risk expenditure of medium amounts of skill and resources produced a moderate performance level.

Resources. Performing the TerfenolD technology transfer took a great deal of time but relatively very little money. The money the PRC spent on conducting the transfer was part of the country's overarching strategy of placing many Chinese students at many universities over a long period of time to collect small pieces of information gradually. FBI reports, expert congressional testimony, and open-source media outlets estimate that recruited agents embedded in academic settings may receive tens to hundreds of thousands of dollars for meaningful technology transfers.[172] Although China sends hundreds of thousands of students to study in the United States each year, a very small fraction are part of the illicit transfer of militarily critical technologies. The monetary cost to China of establishing and maintaining these conduits of information is substantial, but it is orders of magnitude smaller than the United States' native research and development budgets. Additionally, the Chinese company TXRE already had a production line for the kinds of exotic materials like TerfenolD they wanted to create. They simply needed the "recipe"—that is, they needed the additional academic knowledge about how to produce TerfenolD. The resources category thus resulted in a high score for time and a low score for money.

Skill. The PRC relied on a moderate amount of skill to perform the TerfenolD transfer. The PRC needed no more expertise than it already possessed to pursue the information via university students, and there was no additional expertise required to modify the TerfenolD from its transferred state to TXRE's final product (in fact, reports suggested that the final product was lower in quality or a "knock off," implying the expertise surrounding the technology transfer was also relatively low).[173] There was some effort demonstrated by students' pursuit of the production information, and there was also some effort demonstrated in the willingness to use computer hacking methods to market the PRC's version of TerfenolD to Etrema's clients. Hacking Etrema's email server is, however, different in kind from hacking the National Laboratory's technology development computers or file storage. It does not represent a huge amount of expertise but rather a moderate level of effort. Overall, the TerfenolD case scored low in expertise, medium in effort, yielding a medium score for skill overall.

Risk. Unlike in the other cases, the PRC exposed itself to somewhat less risk in the case of the TerfenolD transfer. Although there are restrictions on foreign national students' access to controlled technologies and National Lab programs, the openness and academic freedom that characterize US schools make them a "spy's paradise," according to one former national counterintelligence executive.[174] Such a description implies the relatively low risk of students being found in violation of export regulation licensing laws. The email hacking incident did also expose the PRC to some legal consequences by increasing the threat of detection (as demonstrated by the FBI investigation), although the hacking incident was only tangentially related to the actual transfer of information on TerfenolD manufacturing. Finally, the political risk associated with the TerfenolD transfer was low. Unlike hot-button technological developments like nuclear weapons and cruise missile engines, exotic materials (although strategically valuable) do not engender as much political concern as international treaties on proliferation do. For these reasons, the TerfenolD case scored medium for legal consequences, low for political consequences, and medium overall for risk.

Table 1. PRC Technology Transfer Inputs

Cases	Resources		Skill		Risk	
	Time	***Money***	***Expertise***	***Effort***	***Legal***	***Political***
Cox Report	High	Low	Low	Low	High	High
Garrett Engines	Low	High	Medium	Low	High	High
Terfenol-D	High	Low	Low	Medium	Medium	Low

Source: Author

United States inputs. The inputs required for the cases of technology transfer discussed in this paper stand in stark contrast to the United States' inputs for militarily critical technologies. As summarized in the "Blue" section of Davis and Nacht's *Strategic Latency: Red, White and Blue*, a collection of essays on technology development by the United States and its adversaries, US technology development results primarily from the two main categories of resources and skill.[175] The kind of risks US developers take during native R&D of technologies is not the kind of risk associated with espionage or theft. (There is an element of risk driven by market forces which will be discussed in the Conclusion, but it is risk of a different kind—risk to profit versus risk of legal jeopardy). This thesis does not assume that the United States is always the transferor, nor that the United States is never the transferee; however, for natively developed technologies not obtained through technology transfer, Table 2 summarizes the United States' inputs.

Table 2. United States Technology Development Inputs

Country	Resources		Skill		Risk	
	Time	***Money***	***Skill***	***Effort***	***Legal***	***Political***
United States	High	High	High	High	Low	Low

Source: Author

Performance

Performance within an evolutionary landscape in biology means that survival rates are being compared. In this analysis, performance is a measure of how successful the technology transfer was. Such performance can be measured in a number of ways. This section begins by explaining how performance is scored for this paper and then explains the scores assigned to each instance of technology transfer.

Scoring performance. In breaking down the components of performance that China obtained through technology transfer, this analysis considers gains and losses that resulted from the transfer and treats them as opposite sides of a scale. This method should not be taken to mean that any positive results necessarily balance out any negative ones, but as a generic estimate of the magnitude of performance obtained, this kind of simplification is sufficient. Within the analysis of gains and losses for each case of technology transfer, "technical" and "strategic" outcomes are discussed. In this context, "technical" outcomes refer to material, physical advantages or tactical improvement gained by the transfer. "Strategic" outcomes refer to political gains earned (or political losses suffered) as well as senior leaders' goals met (or unmet).

Importantly, gains and losses are considered within the context of the case, meaning that outcomes are assessed relative to the desired outcome of the transfer, not relative to the state of the technology before the transfer. This is especially relevant for technologies that have a binary, "all-or-nothing" quality. Examples include quantum computing or hypersonic vehicles—a country either does or does not have this technology. Simply attaining faster computing speeds via technology transfer would represent a gain (possibly significant) if compared to the state of technology before the transfer; however, it would be negligible compared to the desired outcome of the transfer if the goal were quantum computing. Likewise, if the goal were to obtain a hypersonic vehicle but only succeeded in improving supersonic speeds, the all-or-nothing aim of having a hypersonic vehicle would remain unmet.

Cox Report. While the PRC gained technically and strategically from the transfer of nuclear weapons information, each gain came with a caveat that dulls the performance edge China sought. The neutron bomb may have been the only truly unmitigated success of the nuclear weapons technology transfer; the test represented a clear technical and strategic improvement. Other improvements, though, were more qualified. Although the transfer moved China's nuclear weapons program forward by years' worth of effort and resources, the transfer did not accomplish its goal of leapfrogging two decades of development in only 10 years. Additionally, the software code China gained was helpful for simulating nuclear tests after the 1996 testing ban; however, not all explanatory components of the code were transferred. In one area, the PRC failed entirely to gain true multiple-warhead MIRV capability via technology transfer. Ultimately, the PRC's strategic aim to move toward a more mobile arsenal, not entirely silo based, certainly did move forward, in part thanks to the technology transfer. Still, with "considerable technical challenges" remaining for China after the Cox Report, this analysis rates performance both technically and strategically as "medium" due to the qualified gains resulting from the technology transfer.

Garrett Engines. The Garrett Engine case also produced mixed performance results for the PRC. Technically, the PRC gained 59 presumably embargoed engines, enabling improvements in components like engine blades, alloys, and hot section technology. Strategically, it gained profound missile technology that would require little modification to employ; however, it remains unclear whether technology from the Garrett Engine case directly led to actual, measurable improvements in China's missile capabilities. Despite these apparent wins for the PRC, it did not achieve the strategic goals it set out to attain via technology transfer, namely freedom from foreign dependency for military aircraft engines. It is possible that the Garrett Engine transfer *combined with other like transfers* moved the PRC's industry forward more broadly, but struggles with aircraft design, integration, and quality control continued to plague Chinese technologists long after the Garrett Case ended. For these mixed results, the Garrett Engine performance scored a medium value technically and a low value strategically.

TerfenolD. The technology transfer in the TerfenolD case resulted in multiple technical and potentially strategic gains. First, the PRC did in fact gain the ability to produce TerfenolD, which was the goal it sought. China appears to be no further ahead of nor behind the United States in developing applications of TerfenolD for military purposes. This gain represents a savings of over 13 years and millions of dollars of US development.[176] Moreover, exotic material piracy like that in the TerfenolD case potentially accentuates China's strategic monopoly on rare-earth elements. Undercutting these gains is the fact that the Chinese variant of TerfenolD was believed to be inferior to the US product. Additionally, the PRC's inability to produce TerfenolD's successor material, Galfenol, may make the strongest argument yet for the value of foundational knowledge and walking the "hard work" path versus the "shortcut" path. The counterargument, of course, is that China may yet be able to obtain Galfenol in the same way, expending no more resources than it has already in the TerfenolD case. Altogether, the gains and losses associated with the PRC's investment in technology transfer of TerfenolD earned a "medium" value for technical performance and a "low" value for strategic performance.

Table 3 summarizes the performance scores for each of the three cases of technology transfer.

Table 3. PRC Technology Transfer Performance Outputs

	Performance	
	Technical	***Strategic***
Cox Report	Medium	Medium
Garrett Engines	Medium	Low
Terfenol-D	Medium	Low

Source: Author

United States performance. A simple way to score the United States' performance in technology development is to think of its performance level as the aiming point of the PRC's technology transfer strategy. Thought of in this way, US performance would *always* be "high," as it is always the best that China could hope to obtain via transfer. This kind of assumption works because of the scope of this analysis—in this study, China is *always* the transferee, and the United States is *always* the transferor (this arrangement is not always true in reality). The assumption also works because this work is entirely retrospective—the analyzer has the benefit of looking back at instances where the US-developed technology was the benchmark sought by China. In other future analyses, this does not have to be the case; however, in such future efforts, Chinese and US performance must be assessed independently of one another. One way to do so might be to assess performance *relative to the goals of the developer.* For instance, in the 2018 Emerging Technology and National Security report, cosponsored by the Office of the Director of National Intelligence and the Department of Homeland Security, a six-month study found that the United States remains highly competitive across key technologies.[177] In this analysis, the United States' performance acts as the standard by which the Chinese technology transfer is measured.

Visualizing the Landscape

To create the evolutionary landscape, each of the input "traits" of a strategy (whether it be technology transfer or native technology development) should be mapped to a different independent dimension and performance measured on an additional dimension. In the classic visualization, a three-dimensional topology results from two input dimensions—moving laterally in the *x* and *y* directions—that produce a third, *z* dimension of elevation representing fitness or performance. The following sections map the evolutionary landscape of the PRC, based on the case studies previously examined, onto different evolutionary landscape visualizations. For easy visualization, it is necessary to combine some inputs into a single dimension. In reality, computational methods would allow for greater granularity of model testing since they could process the higher dimensions needed to account for all inputs. Such future analysis will be discussed further in the Conclusion.

Complex Visualizations

To chart the scores of each of the six inputs (time, money, expertise, effort, legal risk, and political risk) against their resulting performance level, a true evolutionary landscape would require six dimensions for the independent variables and a seventh dimension for the dependent variable. Ultimately, evolutionary landscapes are simply *n*-dimensional graphs of inputs and outputs. Evolutionary landscape expert and technologist Stuart Kauffman created just such a chart of a system that was described by four input variables (each receiving a score of "low" or "high," represented in fig. 4 as a "0" for low and a "1" for high). Kauffman's visualization took the form of a four-dimensional "hypercube," where each vertex (corner) of the shape represented one of the 42=16 possible combinations of input scores. He then ranked each possible combination of inputs and projected them on a chart of higher or lower performance values. Similarly, the six inputs of this paper's notional PRC evolutionary landscape would be computationally understood as a flattened 6-dimensional figure with 729 vertices (the total number of possible combinations of input scores).

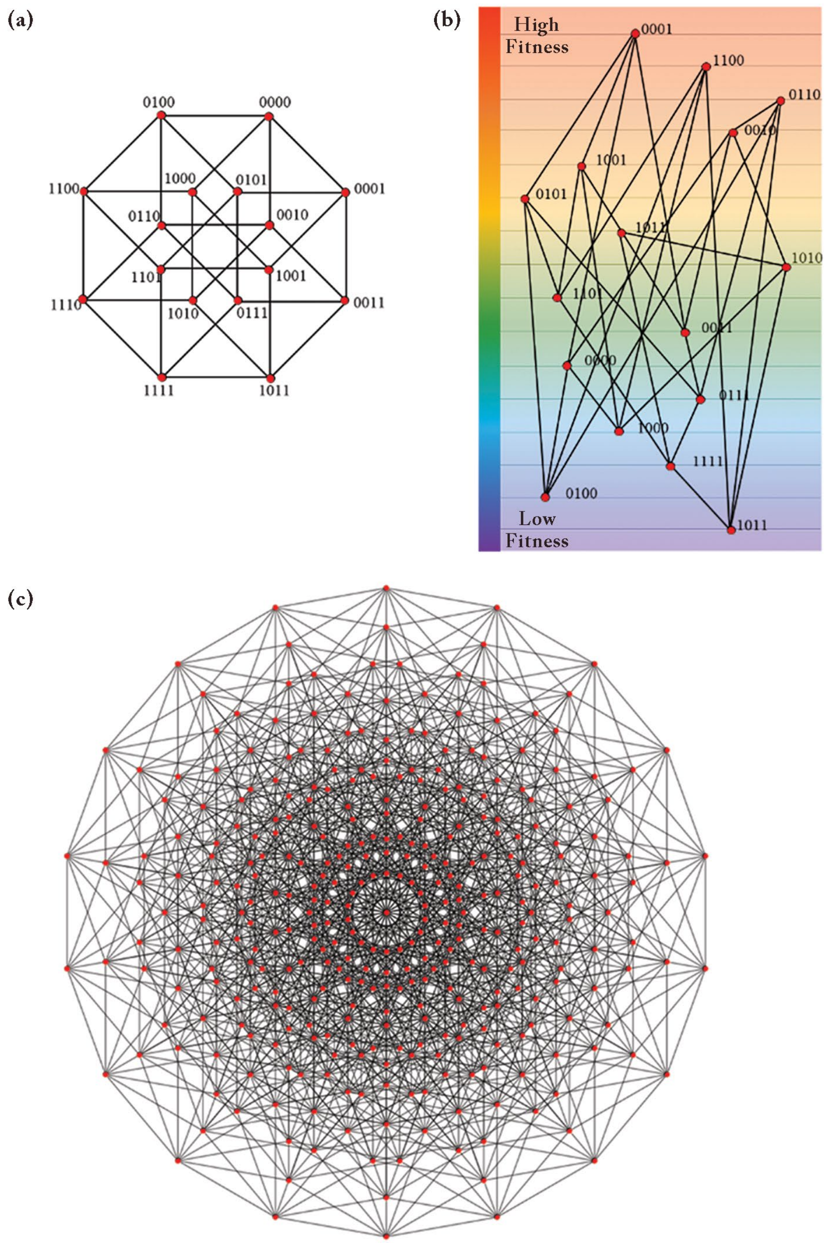

Figure 4. Complex Landscape Visualizations

Source, fig. 4a and 4b: Adapted by the author from Stuart Kauffman, "Technology and Evolution: Escaping the Red Queen Effect," *McKinsey Quarterly* 1 (1995): 118–29. Source, fig. 4c: Thomas Ruen, 3-Generalized-6-Cube, 19 September 2016, https://commons.wikimedia.org/wiki/File:3-generalized-6-cube.svg, used under Creative Commons License.

This study only considers three case studies (with three unique combinations of input scores); thus, three of the 729 combinations of the 6-dimensional landscape have known performance outputs. Using a visualization like that in figure 4c for these three data points yields a relatively information-poor landscape; however, it has promise for future use in large-*n* computational studies.

Simplified Landscape

Kauffman's visualization of an evolutionary landscape is complex and difficult for a decision-maker or policymaker to ingest; however, the landscape is readily digestible for a machine algorithm. Likewise, the 6-dimensional image would be incomprehensibly complicated for a decision-maker or policymaker, though it could form the basis of a computational analysis of the landscape. To generate a readily comprehensible and useful visual model, the next section consolidates inputs to render a simplified landscape in three dimensions.

Consolidating inputs. The case studies suggest six primary inputs for the PRC's pursuit of illegal technology transfer. To visualize these inputs, though, this section consolidates each input into its overarching "category," such that there are fewer dimensions in the visual landscape model. Thus, in table 4, a consolidation of scores for time and money results in an overall score for resources, and a consolidation of scores for expertise and effort results in an overall score for skill.

Table 4. Consolidated PRC Inputs

	Resources		Skill		Risk	
	Time	***Money***	***Expertise***	***Effort***	***Legal***	***Political***
Cox Report	Medium		Low		High	
	High	*Low*	*Low*	*Low*	*High*	*High*
Garrett Engines	Medium		Medium		High	
	Low	*High*	*Medium*	*Low*	*High*	*High*
Terfenol-D	Medium		Medium		Medium	
	High	*Low*	*Low*	*Medium*	*Medium*	*Low*
United States	High		High		Low	
	High	*High*	*High*	*High*	*Low*	*Low*

Source: Author

Separate US and Chinese landscapes. The Literature Review presented a figure of two intersecting evolutionary landscapes (figure 2, reproduced below as the top image in figure 5). In this figure, both landscapes were entirely notional, with no labeled inputs. The PRC's evolutionary landscape that has emerged from the analysis of the three case studies is based on three main categories of inputs for technology transfer: resources, skill, and risk. To depict the PRC landscape in three dimensions, however, one dimension (represented by the z-axis) must be reseverd for performance, the dependent variable. Because risk stands out as the input category most crucially different between the United States' and China's strategies, risk is maintained on its own axis for the PRC landscape. As a final simplifying tool for purposes of visualization, expertise and skill are combined into a single dimension called "capital." To reconstruct the US strategy as if it were on a separate landscape (as in figure 2), risk would not necessitate a dimension since the US strategy, by definition, is engaging in native technology development devoid of the kinds of legal jeopardies associated with illicit technology transfer. Skill and resources in this strategy form the landscape by which the United States ascends peaks of performance. Thus it is possible to reconstruct the "hard work" (native technology development) and "shortcut" (technology transfer) paths to fitness (performance) on separate landscapes that help explain why the PRC, without expending the resources that the United States does, can achieve similar results (figure 5). The simplification involved in this construction, however, combines input categories for the PRC and also fails to show the whole picture of how multiple strategies coexist on a global landscape. The next section reimagines these two landscapes as one, incorporating each input category as its own dimension.

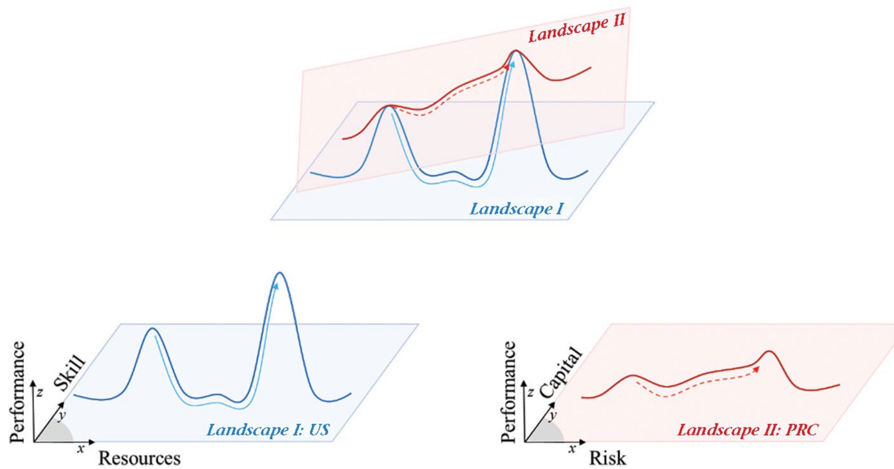

Figure 5. US and PRC evolutionary landscapes for technology development
Source: Author

Combined US and Chinese landscape. It is possible to add a fourth dimension to the current visualization, if color is treated as a dimension (as in a heat map, where color represents an additional dimension of information, such as body temperature or population density). Adding a fourth dimension to the current visual model leaves all three spatial dimensions (x-, y-, and z-axes) available for plotting inputs. With this heat map visualization, all three categories of inputs—resources, skill, and risk—are plotted in space, and performance is indicated by color, with "cooler" colors representing low performance and "warmer" colors representing high performance.

In figure 6, PRC technology development sits at the intersection of three spatial inputs: low skill, moderate resources, and high risk. In this vicinity, the landscape is a cooler green color, indicating moderate performance. US technology development sits at the intersection of high resources (x-axis), high skill (y-axis), and low risk (z-axis). In this vicinity, the landscape is a warmer red color, indicating high performance.

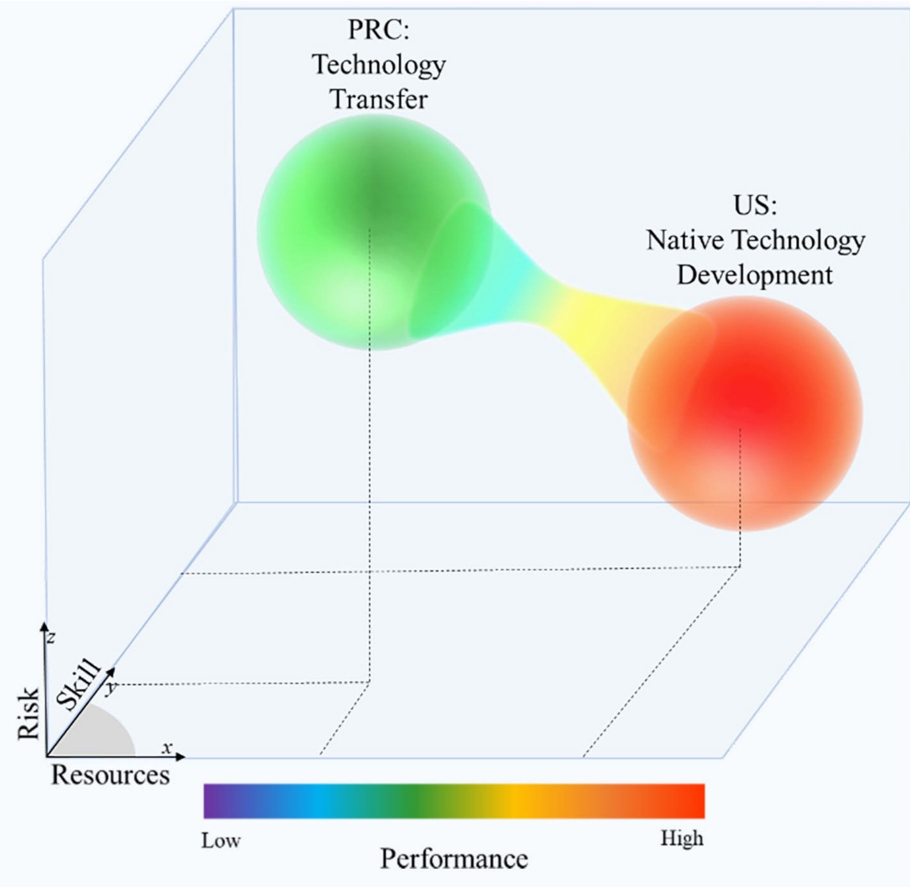

Figure 6. Combined US and PRC, 4-dimensional evolutionary landscape for technology development
Source: Author

The benefit of a visualization like this is that it suggests there is no "contradictory" path between the Chinese and US strategies. It also suggests that the United States is not necessarily situated at the only "hot spot" on the landscape. It is possible that by exploring the "temperature" (analogous to the terrain of 3D landscapes) of surrounding input combinations, the PRC may find it can improve to high fitness via a strategy different from the United States' native technology development route.

Conclusion

The only reward of virtue is virtue.

—Ralph Waldo Emerson, *Essays: First Series*

This paper analyzed three cases of illegal technology transfer from the 1980s to the early 2000s to build evolutionary landscapes representing two competing strategies of technology development: illegal United States). How does this analysis answer the research question: technology transfer (China) and native technology development (the *How does Chinese technology transfer deviate from the evolutionary landscape paths traversed by US technology development?*

First, the analysis categorized the kinds of inputs (traits) required for each strategy. Next, it assessed the inputs' resulting performance levels. Finally, these dimensions were mapped to evolutionary landscapes. The most important way in which the PRC and US strategies diverged was their treatment of legal and political risk as well as the amount of capital (skill and resources like time and money) each spent on their technology development strategy. For the PRC, the technology transfer strategy produced medium performance results while the United States' native technology development strategy produced high performance results.

This section examines the meaning, implications, and possible future extensions of this study's analysis.

Summary of Cases

The meaning gleaned from these case studies centers on the value of capital inputs (like time, money, expertise, and effort) versus the value of taking legal (or political, not to mention ethical) risks to get ahead in performance. The analysis also enabled the construction of an evolutionary landscape as a visualization tool for comparing two technology development strategies.

Instances of illegal technology transfer by China studied in this paper generally required relatively low capital and relatively high risk. The kind of risk involved was legal jeopardy or political consequence (e.g., violating a treaty). Such inputs generally produced moderate performance compared to the aiming point, which was attainment of US-quality technologies. Some experts believe that China's illegal technology transfer strategy necessarily results in moderate performance because "copying and emulating foreign designs . . . does not confer ability to design and manage [technology development]; on the contrary, it can impose path-dependent limitations that lead to dead ends or substandard, poorly integrated systems."[178] One of the benefits of considering technical and strategic gains and losses in performance independently is that it allows for the possibility that the transfer resulted in good technical performance without attaining the transfer's strategic goals (or vice versa). This level of analysis adds nuance to experts' evaluation of technology transfer outcomes.

In all, the analysis of these three case studies allowed for several generalizations about technology transfer: (1) in these cases, the transfer strategy always involved greater risk than native development (not a surprising finding), (2) increased risk was always the trade-off associated with the transfer strategy's decreased inputs in capital like time/money resources and human skill, and finally (3) no amount of risk taken was able to make up for the performance lost by decreasing capital inputs compared to the "hard work" strategy.

Implications of the Evolutionary Landscape

The evolutionary landscape constructed in this analysis serves as a helpful visualization tool to compare strategies. Comparisons on a landscape also enable the prediction of how different technology development strategies might play out for the United States or whether the US's current strategy to counter Chinese technology transfer is effective.

Visualization

The benefit of using evolutionary landscapes to visualize competing technology development strategies is not in their exactness but rather in their ability to suggest connections that were previously invisible. Evolutionary landscapes with enough input traits can become less and less categorical, incorporating a multitude of complexly interacting factors into an n-dimensional model. Such a model prevents viewers from getting hung up on any one input, instead considering the behavior of the complex system as a whole. Visualization makes certain connections or even certain gaps more apparent. For instance, examining the two separate landscapes built for the American and Chinese technology development strategies might raise the question whether, while the US strategy does not currently incorporate legal risk, should it incorporate some other kind of risk? In the landscapes constructed in figure 5 (reproduced as the top image in figure 7 below), the US's low- or no-risk technology development strategy only considers the kinds of risks China ran, like violating international treaties or laws. The bottom image in figure 7 suggests another way to view the US's risk. In this image, the US takes market risks to achieve technological performance, while the PRC takes institutional (legal and political) risks to steal technologies. Visualization of strategies on a landscape enables the analyst and decision-maker to identify new hypotheses for future research.

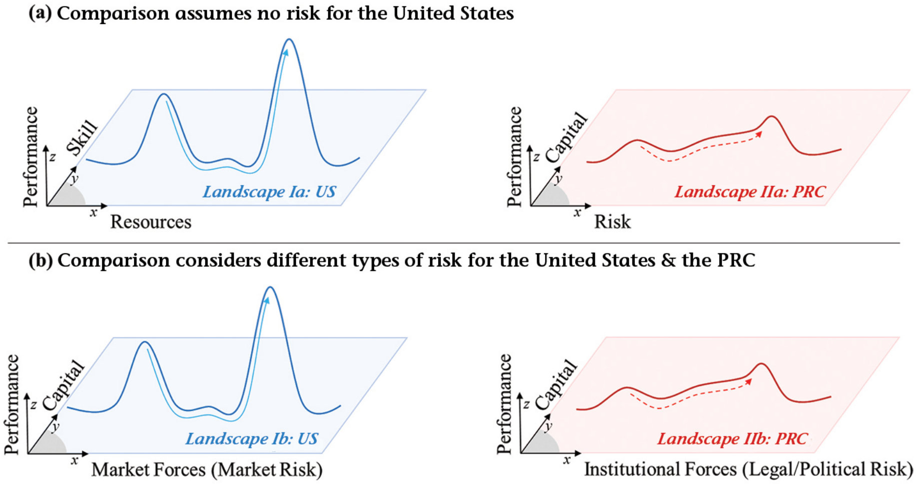

Figure 7. Using visualization to make additional connections
Source: Author

Strategy

Using evolutionary landscapes enables strategists to see other ways of characterizing the competition between two states' technology development strategies. One way strategists can view technological competition is through an "offense" vs. "defense" lens. Offense refers to the US's willingness to *do* technology transfer as the transferee; defense refers to the desire to guard against others' attempts to transfer technology from the United States. Another evolutionarily inspired way to view technological competition is through the lens of mutualism—wherein two apparently competing parties benefit from each other's improvements.

Offense. This study raises questions about whether the US should consider pursuing an "offensive" technology transfer strategy if similar results could be obtained at lower cost. Could the capital spent on natively developing technologies that don't generate a large performance gap (or for which there is no advantage to developing it first) instead be spent on skills like reverse engineering? This strategy would require a significant change in mindset as well as the setting aside of certain ethical or cultural norms. Americans would have to set aside two categories of norms: ones governing what we believe is taboo and ones that create our image of ourselves. Self-governing norms include beliefs about integrity and intellectual property. These norms essentially say the US should not steal. Image-creating norms are those that say the US should always be the "first," "most," "best," or "only" in developing cutting-edge technologies. These norms push us to favor native development over technology transfer because we do not want to be the ones chasing another country's better technology. Such norms ignore that for some technologies, it may not matter which country develops them first (they confer no first-mover advantage). If strategists truly view technology development as an international, zero-sum competition, then it might pay to find the conditions under which an offensive technology transfer strategy performs as well as or better than the native development strategy.

Defense. Similarly, in a zero-sum game with a competitive approach to technology transfer, the US's defensive stance may also change in response to this evolutionary landscape analysis. An evolutionary landscape of technology transfer that incorporates multiple dimensions of inputs can point to the individual traits or interactions of traits that produce higher performance in the PRC. For the United States, this implies an ability to focus its protective efforts on specific aspects of the landscape instead of broadly increasing legal risk with stricter legislation, regulation, and enforcement. Currently, the United States applies the same rules across the board for all technologies it deems militarily critical. Those rules are designed to prevent the sale or theft of technologies; however, the rules only target other states' legal risk. If the PRC maintains a certain balance of skill and resources in the majority of its high-risk technology transfers, then (a) risk might not be a factor in its decision-making and (b) if the United States can disrupt the balance of the PRC's other inputs, that may disrupt the technology transfer strategy. Seen this way, evolutionary landscapes serve as intricate yet holistic tools to perform COG analysis.

Mutualism. Lastly, the biological origins of evolutionary landscapes as a tool for understanding strategy suggest that the zero-sum competition assumption may itself be incorrect. There are biological strategies where two apparently competing organisms find their highest performance peaks when they cooperate with each other in some way. These kinds of relationships are called mutualistic. Technology transfer already implies that one party is gaining from another's inputs; what should then arise, in deeper (computational) analysis of the evolutionary landscape, is that the dependent party (the transferee) does *best* when the transferor is "healthy" or performing well. If the PRC is dependent on the US for the performance of certain militarily critical technologies, then, paradoxically, China should have an interest in the advancement of technology in the US. Evolutionary landscapes like those constructed in this paper have serious implications for how strategists view the interaction between states like China and the US. Future research can help turn those visualizations and strategic frameworks into even stronger data-driven analytical tools.

Future Research

One of the goals of future research in this vein should be to minimize or eliminate assumptions and limitations of the current study. Another ought to be improving the mechanics of the model. Finally, the results of this study could be made more powerful with quantitative testing of the model.

Broadening the Scope

Growing the number of studied cases of technology transfer helps eliminate the limitations of time and geography in this study. There are many more instances of technology transfer that could be compiled into a large-*n* case study. Such a study could incorporate instances of technology transfer where the United States or other countries are transferees of technology to try and determine whether differences in risk inputs depend on characteristics of the countries involved and their relationship to one another. Eliminating the temporal scope limitations of this study may also prove enlightening. For example, a study that looked at technology transfer over time may show increasing efficiency in technology transfer if countries like China are getting better at performing it, or decreasing efficiency if countries like the US are getting better at defending against it.

Fine-tuning the Model

One way of fine-tuning the evolutionary landscape model is to account for more inputs or traits. This method could look at breaking out the inputs of time, money, effort, expertise, legal risk, and political risk into smaller subcomponents—essentially turning a six-dimensional landscape into an *n*-dimensional one. Such a landscape would surely be almost impossible to visualize, but it would not be impossible for computational methods to evaluate. Such fine-tuning requires a smart balance between a model that is complex enough to account for the complexity of the system and a model that is simple enough to be understood.

Another way to fine-tune the model would be to add characteristics to technology performance—one characteristic of particular interest is technologies that have (and those that do not have) a "first-mover advantage." In some cases, it pays to be the first one to develop a technology—in other cases, being first may matter less than being best qualitatively. In still other cases, the importance of being the first, most, best, or only could be so insignificant as to make increases in developmental input disadvantageous. These are the kinds of caveats that can be added to the model with more research on the value of performance obtained through technology transfer.

Quantitative Testing

Perhaps the biggest step future research on this topic could take is quantitative testing of the evolutionary landscape model. This would mean putting together a fitness function that faithfully reproduces the inputs and performance shown across many cases of technology transfer. The benefit of having such a model could be to provide data-driven recommendations to decision-makers about which posture the United States should pursue for developing different kinds of critical technologies. Quantitative outputs might look like measures of performance relative to strategic goals, or they might look like the expected amount of capital needed to produce a certain level of performance.

Another quantitative output could be a comparison of amounts of capital and skill input to acquire technologies first (before other countries can do so). For instance, it may confer no additional strategic benefit to attain a non-first-mover advantage technology as fast as possible. The United States could instead spend the capital saved on those technologies for use in natively developing the technologies with clear first-mover advantages. The United States would in such instances have to pursue an offensive technology transfer strategy that might include, for example, standing up a reverse engineering center at a national laboratory.

The conceptual model developed in this paper gives strategists a new way to think about the US's technology development strategy. Quantitative testing could provide numeric measures to enrich those new perspectives.

Desired Goals

It is my hope that in future years, scholars and strategists will tackle each of the future research goals listed here, with an ultimate goal of more fully describing the ecology of technology transfer. The results of such future research would find their best home in the hands of senior military and civilian national strategists and policymakers. Equipped with a fine-tuned, broadly scoped, and rigorously tested model, such leaders will be able to approach technology development with both the confidence and intellectual curiosity of a practiced naturalist on a new landscape.

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

1. The US military operates in the domains of air, land, sea, space, and cyberspace. Each of the military services is responsible for organizing, training, and equipping its services to achieve superiority over the US's adversaries in these domains. Superiority can be achieved by a combination of organization (i.e., personnel, institutions, and doctrine), training, and equipment (i.e., generating and maintaining those cutting-edge technologies which will advance our capabilities beyond those of our adversaries). This study deals primarily with the development of technologies that bestow just such a domain superiority advantage.

2. Blanken, Rothstein, and Lepore, eds., *Assessing War*.

3. Blanken and Lepore, "Slowing Down to Keep the Lead," 317–34.

4. The theory of an enemy (or friendly) center of gravity comes from Carl von Clausewitz's *On War* (where he terms it *Schwerpunkt* in the text's original German). Clausewitz's intent was to describe the single most vital point of the enemy—the point (a place, a person, a capability, even an idea) that, if targeted, would cause the enemy's ultimate defeat. In modern US joint warfighting doctrine, as well as in the doctrine of each service, "COG analysis" is one of the central war planning steps. Clausewitz, *On War*; and Kornatz, "The Primacy of COG Planning."

5. Smith, Jeter, and Westgaard, "Three Approaches to Center of Gravity Analysis."

6. Pike and Zagorowski, "Dense Urban Areas."

7. Hart and Ferguson, "Empirical Fitness Models."

8. Additionally, this paper does not assume that the US is *always* the transferor of technology (many other countries also experience illicit technology transfer as unwilling transferors), nor does this paper assume that the United States is *never* the transferee (there may be instances where the United States has engaged in illicit technology transfer aimed at another state). This study, though, analyzes only one kind (and one directionality) of transfer.

9. Marks, Gerrits, and Marx, "How to Use Fitness Landscape Models," article number 7.

10. Brown and Singh, "China's Technology Transfer Strategy."

11. Revolutions in military affairs are points or periods in history wherein massive changes or advances in military technology, strategy, or capability have fundamentally altered the way war is waged.

12. Organización Mundial de la Propiedad Intelectual, *Licensing Guide for Developing Countries.*

13. Lan, *Technology Transfer to China*, 23.

14. Atkinson, "Understanding the U.S. National Innovation System." For an excellent, brief overview of the history of innovation in the US, consider Atkinson's summary of major phases in US technology development in pages 3–6 of this article.

15. Committee on Homeland and National Security of the National Science and Technology Council, "A 21st Century Science, Technology, and Innovation Strategy"; and Committee for National Security of the National Science and Technology Council, *National Security Science and Technology Strategy* (editor's note: Since this paper was written, the *US National Defense Science and Technology Strategy 2023* has been released, https://www.cto.mil/.

16. DuBois, Gerstein, and Keagle, *Science, Technology, and U.S. National Security Strategy*.

17. Lan, *Technology Transfer to China*, 30.

18. Heller, *Technology Transfer and Human Values*, 1–6.

19. Heller, 334–41.

20. Defense Institute of Security Cooperation, *The Management of Security Cooperation*, 7-4; and Heller, *Technology Transfer and Human Values*, 4–5.

21. Chen, *Managing International Technology Transfer*, 5.

22. Johnson, "Seller Beware," 1.

23. Heller, *Technology Transfer and Human Values*, xi.

24. Rubin, "United States Export Controls," 633.

25. Defense Institute of Security Cooperation, *The Management of Security Cooperation*, 7-2–7-4.

26. Government Accountability Office, "Protecting Defense Technologies," 23.

27. Defense Institute of Security Cooperation, *The Management of Security Cooperation*, 7-4.

28. Defense Institute of Security Cooperation, 7-5.

29. Stephen Coulthart et al., "Emerging Technology and National Security," 2.

30. US Congress, Office of Technology Assessment, "Technology Transfer to China," 21.

31. US Congress, Office of Technology Assessment, 31, 40–41.

32. Known variously as the "human wave," "mosaic," or "thousand grains of sand" approach, this concept refers to China's nontraditional intelligence gathering tradecraft wherein information is collected on a piecemeal basis, one "grain of sand" at a time. Wise, *Tiger Trap*; and Hannas, Mulvenon, and Puglisi, *Chinese Industrial Espionage.*

33. Wise, *Tiger Trap*, 13.

34. Hannas, Mulvenon, and Puglisi, *Chinese Industrial Espionage*, 2.

35. Fravel, "Revising Deng's Foreign Policy."

36. Kan, "China's Military-Owned Businesses," CRS-1.

37. Brown and Singh, "China's Technology Transfer Strategy," 3.

38. Office of the United States Trade Representative, "Update Concerning China's Acts, Policies and Practices," 3.

39. Office of the United States Trade Representative, 3–4.

40. Mizokami, "China Cloned the M16."

41. Mizokami, "China Cloned the M16;" and Kondapalli, "Toward a Lean and Mean Army," 461–77.

42. Bennett and Bender, "How China Acquires 'the Crown Jewels' of U.S. Technology."

43. Wright, "The Roles of Mutation, Inbreeding, Crossbreeding and Selection in Evolution," 356–66.
44. Example adapted from Benkman, "Divergent Selection," 1176–81.
45. Dietrich and Skipper, "A Shifting Terrain," 1.1–1.6.
46. Dietrich and Skipper.
47. Gerrits and Marks, "The Evolution of Wright's (1932) Adaptive Field," 459–79.
48. Gerrits and Marks.
49. Gerrits and Marks.
50. Kauffman, "Technology and Evolution," 118–29.
51. Hobcraft, "Introducing the Innovation Fitness Landscape Model."
52. Green, "Complex Adaptive Systems in Military Analysis."
53. Murphy, "Complex Adaptive Systems and the Development of Force Structures."
54. Beckerman, "The Non-Linear Dynamics of War."
55. Pigliucci, "Landscapes, Surfaces, and Morphospaces," 3.1–3.4.
56. Gerrits and Marks, "The Evolution of Wright's (1932) Adaptive Field," 466.
57. Office of the National Counterintelligence Executive, "Annual Report to Congress on Foreign Economic Collection and Industrial Espionage 2001."
58. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China."
59. Johnston et al., "The Cox Committee Report."
60. Cox, vol. 1, chap. 2, 66.
61. Cox.
62. Cox, vol. 1, chap. 2, 69.
63. Medalia, "Chinese Nuclear Testing."
64. Cox, vol. 1, chap. 2, 77.
65. Cox, vol. 1, chap. 2, 60–61.
66. Panofsky, "Assessing the Cost vs. Benefit of U.S.-Chinese Scientific Cooperation," 30–36.
67. Cox, vol. 1, chap. 2, 82.
68. Cox, vol. 1, chap. 2, 71.
69. Cox, vol. I, chap. 2, 83.
70. Cox.
71. Cox, vol. 1, chap. 2, 69.
72. Specter, "Report on the Investigation of Peter Lee."
73. Cox, vol. 1, chap. 2, 88.
74. Cox, vol. I, chap. 2, 88–89.
75. Specter, "Report on the Investigation of Peter Lee."
76. Cox, vol. I, chap. 2, 73.
77. Gertz, "Pentagon Confirms China's Missile Test."
78. National Air and Space Intelligence Center, "Ballistic and Cruise Missile Threat."
79. Fisher, "Evidence Emerges of Possible DF-31 ICBM Variant."
80. Cox, vol. I, chap. 2, 66.
81. Cox, vol. I, chap. 2, 81.

82. Cox, vol. I, chap. 2, 60.
83. Cox, vol. I, chap. 2, 68.
84. Cox, vol. I, chap. 2, 85
85. Cox.
86. Cox, vol. I, chap. 2, 61–62.
87. Cox, vol. I, chap. 2, 61.
88. Cox.
89. Cox, vol. I, chap. 2, 72.
90. Cox, vol. I, chap. 2, 82.
91. Cox, vol. III, chap. 10, 123.
92. Cox, vol. III, chap. 10, 124.
93. "Hot sections" and other technical details of jet engines relevant to this case study are discussed in greater detail in later paragraphs of this background sub-section.
94. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 125–27; and Leitner, "PRC Gas Turbine Acquisition Efforts."
95. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 3.
96. Farnham, "America's Leading Exporters," 72.
97. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 3.
98. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, 5–6.
99. Distinct from the common US military acronym COCOM, which refers to the United States Unified Combatant Commands. This thesis uses the alternative capitalization "CoCom" to refer to the international organization established during the Cold War to embargo Eastern bloc countries.
100. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 129.
101. Unknown (presumably Defense Technology Security Administration), "Garrett TurboFan Engines to China."
102. Swaine, "China: Domestic Change and Foreign Policy;" and Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 84.
103. Collins and Erickson, "Jet Engine Development in China."
104. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 124.
105. George, "Full Authority Digital Engine Controls," 114–16.
106. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 132.
107. Griffin et al., "Engineering Analysis and Technical Policy Recommendation of General Exception Status," 8.

108. Unknown (presumably Defense Technology Security Administration), "Missile Tech Implications of Garrett TFE-731-2A-2A/TFE-731-3 Technology Transfer to the PRC."

109. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 9.

110. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, 9–10.

111. Griffin et al., "Engineering Analysis and Technical Policy Recommendation of General Exception Status," 1.

112. Griffin et al., 1–2.

113. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 11.

114. Griffin et al., "Engineering Analysis and Technical Policy Recommendation of General Exception Status," 8.

115. Griffin et al., 7.

116. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 12.

117. Griffin et al., "Engineering Analysis and Technical Policy Recommendation of General Exception Status," 5–6.

118. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 16–18.

119. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 140–41.

120. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 20.

121. Lachica, "Allied Signal Ends Plan to CoProduce Engines."

122. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 23–25.

123. Lachica, "Allied Signal Ends Plan to CoProduce Engines."

124. Elder, Sutter, and Kulina, "License Production Control Plan (LPCP)."

125. Collins and Erickson, "Jet Engine Development in China."

126. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 137.

127. Axe, "Engine Woes Could Ground China's Stealth Armada;" and Collins and Erickson, "Jet Engine Development in China."

128. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 81.

129. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 12.

130. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, 14.

131. Griffin et al., "Engineering Analysis and Technical Policy Recommendation of General Exception Status," 1; and Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 9.

132. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 137.

133. Unknown NSA employee (possibly Curtis Jordan) and Unknown Fort Lee employee, "You Don't Know Who You Are Dealing With—Choose Another Topic," 20; and Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. III, chap. 10, 143.

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135. Huff, 3.

136. Unknown (presumably Defense Technology Security Administration), "Garrett TurboFan Engines to China."

137. Unknown (presumably Defense Technology Security Administration).

138. Unknown (presumably Defense Technology Security Administration).

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140. Leitner.

141. Collins and Erickson, "Jet Engine Development in China."

142. Schopfer, "TFE731-2A-2A Engines for China K-8 Trainer."

143. Collins and Erickson, "Jet Engine Development in China."

144. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. I, chap. 1, 10–12.

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148. Wheeler.

149. Daniels, "Scientists in Iowa Have Developed a Magic Metal."

150. US Department of Defense, "Annual Report on the Military Power of the People's Republic of China," 39.

151. Wheeler, "PRC Espionage Leads to 'Terf' War."

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154. Wheeler, "PRC Espionage Leads to 'Terf' War."

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167. Wheeler, "PRC Espionage Leads to 'Terf' War."

168. Cox, "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," vol. I, chap. 2, 66.

169. Cox, vol. I, chap. 2, 81.

170. Griffin et al., "Engineering Analysis and Technical Policy Recommendation of General Exception Status," 1.

171. Collins and Erickson, "Jet Engine Development in China"; and Axe, "Engine Woes Could Ground China's Stealth Armada."

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175. Davis and Nacht, *Strategic Latency*.

176. Wheeler, "PRC Espionage Leads to 'Terf' War"; and Daniels, "Etrema's Magic Metal."

177. Coulthart et al., "Emerging Technology and National Security."

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Abbreviations

AECA	Arms Export Control Act
CATIC	China National Aero-Technology Import/Export Corporation
CCP	Chinese Communist Party
COG	center of gravity
DEEC	digital electronic engine controller
DOC	Department of Commerce
DOD	Department of Defense
DTRA	Defense Threat Reduction Agency
DTSA	Defense Technology Security Administration
ELT	extended life turbine
FAA	Federal Aviation Administration
FADEC	full authority digital engine controls
GED	Garrett Engine Division
IC	intelligence community
ITAR	International Traffic in Arms Regulations
MCTL	Militarily Critical Technologies List
MIRV	multiple independently targetable reentry vehicle
NORINCO	North Industries Group Corporation Limited
PLA	People's Liberation Army
PRC	People's Republic of China
R&D	research and development
RMA	revolution in military affairs
SAIC	Science Applications International Corporation
TXRE	Gansu Tianxing Rare Earth Functional Materials Co. Ltd.
US	United States

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