Military Technology Races

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Introduction

Because of the nature of modern weapons, significant innovations in arms technology have the potential to induce dramatic changes in the international distribution of power. Consider, for example, the "strategic defense initiative" (SDI), a program initiated by the United States in the early 1980s. Had the program been successfully completed, it might have led to a substantial devaluation of Soviet nuclear capabilities and put the United States in a very dominant position. It should not then come as a surprise that interstate rivalry, especially among super powers, often takes the form of a race for technological superiority. Mary Acland-Hood claims that although the United States and the Soviet Union together accounted for roughly half of the world's military expenditures in the early 1980s, their share of world military research and development (R&D) expenditures was about 80 percent.[1] As further proof of the perceived importance of R&D, note that whereas the overall U.S. defense budget increased by 38 percent (from $225.1 billion to $311.6 billion in real terms) from 1981 to 1987, military R&D spending increased by 100 percent (from $20.97 billion to $41.96 billion).[2] Moreover, before World War II military R&D absorbed on average less than 1 percent of the military expenditure of major powers,[3] but since then it has grown to 11–13 percent.[4] The emphasis on military technology is bound to become more pronounced in the future as R&D becomes the main arena for interstate competition.

In this article I examine the properties of international military R&D competition when military technology affects the distribution of power. I develop a dynamic

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1. Acland-Hood 1984.
2. Weinberger 1986, 313.
3. SIPRI 1974, 127.
4. Acland-Hood 1986, 23–30.

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model in which two nations "compete" for the development of a new weapon in a multistage race and where R&D is costly and its outcome uncertain. Although the model is based on a well-known model of commercial R&D competition,[5] when factors related to distribution of power are considered, military and private technology races differ significantly from commercial competition.

I address a set of questions pertaining to R&D spending as nations move successively, whether simultaneously or not, through the various stages of a technological race. In particular, I study how the amount of resources devoted to weapons R&D changes as a nation pulls ahead, falls behind, or catches up with a rival or as a nation moves closer to successfully completing the development process. Do nations spend relatively more on weapons development when they are in the lead or when they are lagging behind? How does the intensity of effort change as the technological gap increases? Does technological parity encourage or discourage R&D efforts? How do imitation possibilities affect spending in the various stages of development? Providing answers to these questions will enhance our ability to explain and predict the intensity as well as the results of existing and future military rivalries in terms of observable technological (and other) factors.

The practical importance of this analysis can hardly be overestimated. For example, how will weapons development programs in India and Pakistan be affected by China's effort to close its military technological gap with the United States? Will the intensity of the nuclear development programs in the Middle East accelerate or decelerate if the Arab states close the technological gap with Israel? Will China's emergence as a challenger to the United States intensify weapons development programs? The importance of these questions for the distribution of military capabilities and hence the probability of war (as determined, for instance, by such theories as the balance of power) is obvious. As far as I know, no formal models yet exist in the literature to address such questions.

The predicted race dynamics vary considerably with the type of weapon considered and the characteristics of the nations involved in the race. The typical patterns for races where preemption by the winner is ruled out and catching up technologically is of critical importance for the distribution of power are as follows: The race begins with the two competitors spending modest amounts on R&D. A breakthrough by one nation stimulates higher spending in both nations, with spending increasing dramatically in the laggard nation. The laggard intensifies effort even more if it falls further behind or if the leading nation completes development. If, on the other hand, the laggard nation manages to catch up, it relaxes effort somewhat, whereas the leading nation redoubles effort. Finally, a tied race becomes more intense the closer the rivals get to completing development.

I evaluate the empirical relevance of this theory (and hence its practical usefulness) by examining its ability to match the actual patterns observed during the U.S.–Soviet missile and antiballistic missile (ABM) systems race. The key implication of the model is how the level of R&D spending varies with changes in a nation's rela-

5. Grossman and Shapiro 1987.

tive position in the race. In particular, the theory predicts that weapons development programs in the United States accelerated as a result of perceptions of either falling behind or losing its lead and decelerated as a result of perceptions of surging ahead of the Soviet Union. The study of the actual race reveals a close match with the theory. This finding suggests that concerns about the distribution of power are an important determinant of military R&D spending. Existing theories of military R&D programs (such as the theories of bureaucratic politics, military-industrial complex, and the technological momentum) tend to discount the role of such "national interest" motives.

I first offer a brief literature review and then describe the model. Using numerical simulations, I address the questions raised earlier regarding the intensity of R&D in the different stages of the race. I conclude by discussing the empirical content of the theory.

Literature Review

Interstate technological races have been studied mostly within the arms race literature. Samuel Huntington draws a distinction between qualitative arms races, where competition involves developing new forms of military force and generating technological breakthroughs, and quantitative races, where competition simply involves expanding existing forms of military capabilities.[6] Huntington asserts that qualitative races may be more desirable from the standpoint of international stability because of their greater power of deterrence. Michael Intriligator and Dagobert L. Brito challenge this view.[7] They argue that quantitative races insure nations against the possibility that some technological innovation will render them incapable of an effective retaliatory second strike (that is, if they have a large number of weapons, enough will probably survive a first strike to allow them to strike back). Technological races, on the other hand, are dangerous because they may give rise to a revolutionary technological breakthrough that renders a first strike attractive (to use the familiar Richardsonian terms, technological improvement can lead to instability by both shrinking the region of deterrence and expanding the region of war initiation). D. S. Sorenson discusses how technological changes in weapon characteristics affect arms race stability.[8] He notes that since a major technological breakthrough is always possible, competitors in an arms race will invest heavily in military R&D to minimize uncertainty, a fact that may well lead to arms race instability and higher overall levels of arms capacity. Finally, Michael Wolfson stresses how uncertainty can lead to escalation.[9]

These studies are exclusively concerned with the implications of technology for international stability and the probability of war and pay little attention to the charac-

6. Huntington 1958.
7. Intriligator and Brito 1976 and 1984.
8. Sorenson 1980.
9. Wolfson 1985.

teristics of technological rivalry and the process of weapons development. In particular, there has been no discussion of such important issues as where new weapons are coming from (namely, that they are the purposeful but uncertain outcome of R&D efforts), what determines military R&D spending, or how a nation's relative and absolute position in the technological ladder influences the intensity of competition and hence the rate of introduction of new weapons. The only formal treatment of technological choice in a dynamic setting that I am aware of is that by Yukiko Hirao,[10] who deals with one particular aspect of technological choice, namely, quantity versus quality. Hirao assumes the existence of two steps in technological decisions: first, a nation (or its defense establishment if the latter pursues its own interests) decides on the quality of weapons to be acquired; second, it decides on the quantity of weapons.

The Theory

I study the behavior of two nations competing for the development of a particular new weapon that can significantly affect military capabilities and the distribution of military power. The weapon sought could be a single one or a system of related weapons, offensive or defensive; it may represent an improvement of an existing weapon or it may be a completely new system; it may be easily producible or not; and so on. Typical examples are the atomic bomb, the MIRVs (multiple independent reentry vehicles), the ABM systems, and a space-stationed "super-laser" gun.

To understand the characteristics of the race one must specify (1) the "supply" side (that is, the cost and the technical aspects of the development process), (2) the "demand" side (that is, the benefits accruing from this particular weapon that make its development desirable), and (3) the rules of the competition (that is, how each side perceives and reacts to its rival).

The starting point for understanding the "supply" side lies in recognizing that weapons development is a complex process (at least for major weapons) whose completion typically requires going through various stages and overcoming important intermediate hurdles, each presenting its own difficulties and uncertainties and each serving as a prerequisite for the final product. In each of these stages, scarce resources must be employed. Although the more one spends the greater the likelihood of success, there is no guarantee that one's efforts will meet with success.

To capture this process in a tractable way, I will require that the development of a weapon must go through three successive stages. In the initial stage, stage 0, no significant progress has been made. For instance, MIRVs were in stage 0 before restartable rocket motors and vernier vehicles were developed.[11] In the next stage, stage 1 (whose completion is a prerequisite for moving to the final stage), a nation

10. Hirao 1994.

11. A MIRV is a missile that carries multiple warheads, each able to be separately aimed and targeted. The warheads are placed on a "bus" (a post-boost vehicle that carries and releases the reentry vehicles (RVs) at precise times and directions) that is equipped with its own inertial guidance system and several motors that can be used to change its orientation and velocity. The restartable rocket motors allow each RV

has achieved a breakthrough in the form of an intermediate result, but significant uncertainty still remains concerning its ability to successfully complete development. The intermediate result may or may not have any value on its own, depending on the range of its applications (for instance, the restartable rocket motor that made MIRVs possible was initially developed for NASA). In the final stage, stage 2, all remaining hurdles have been overcome and the sought-after weapon has (or can easily) become available.

A three-stage specification is adopted for two reasons. First, it is realistic. For example, the development of a relatively small thermonuclear warhead in 1953 was the necessary intermediate step that made long-range ballistic missiles possible, and the construction of an operational "bus" mechanism was the key engineering development necessary for MIRV systems. Second, it serves as a means of modeling a nation's absolute position (how close it is to completing the project) and its relative position (how far it is ahead of its rivals) in a race. Adding multiple intermediate steps is feasible but very cumbersome and, as has been demonstrated elsewhere, does not add any new insights relative to the single intermediate step specification.[12]

Finally, besides engaging in original R&D efforts, nations may employ another means of arriving at the desired result, namely, imitation ("espionage"). I will assume that nations may be able to, perhaps imperfectly, copy technologies developed elsewhere.

Summarizing the "supply" side: a nation can develop a new weapon either with original R&D or with imitation activities. R&D involves successive stages, is subject to uncertainty, and its probability of success can be increased by additional spending.

Now we turn to the "demand" side. A new weapon is conceived either as a response to a perceived threat or as a possible source of creating an advantage vis-à-vis one's competitors. In either case, there are payoffs to the development of the weapon that motivate the race. These payoffs may capture anything that nation finds valuable about the weapon, such as economic resources of other nations that may become prey to the new weapon, personal prestige that may accrue to the nation as a result of success (such as completing the first trip in space), or the ability to use the new weapon as a "bargaining chip" in future arms control negotiations.

The "value" of the weapon depends on its type, on whether the other side has already developed or is close to developing it, and, finally, on the characteristics of the nation (location, type of political system, existing capabilities, other weapons possessed, type of adversaries, and so on). There is no such thing as a weapon in abstract; instead, a particular weapon (say, a hydrogen bomb) has certain features, is possessed by a particular nation (say, an expansionist military regime), and may or may not be possessed by that nation's adversaries. A weapon may be valuable to a particular nation only as long as its rival does not have it (for example, a nuclear

to be placed on a different trajectory (the main engine must stop and start again). The vernier vehicles allow the trajectory of the MIRV to be adjusted.

12. Harris and Vickers 1987. In other words, three stages suffice to define absolute and relative position in the race as well as distance from the finish line.

bomb to Nazi Germany); or its value may not be significantly compromised by simultaneous foreign possession (for example, a nuclear bomb developed purely for deterrence purposes). Although it may seem that different models would be needed for different types of weapons, it will become clear shortly that all of the cases described earlier can be analyzed within a single model by choosing the appropriate payoff structure. I find this property of the model very appealing.

Finally, concerning the rules of the race, I make two assumptions about perceptions and interactions. First, I assume that each side knows how far the other has advanced. Allowing for incomplete information is straightforward. It can be done by replacing actual with expected values as long as strategic interaction in the form of signaling, belief manipulation, and so on, is ruled out (such considerations are certainly interesting, but their introduction would create formidable technical difficulties[13]). The most interesting aspect of expectations is that the patterns of weapon races described in this article can be generated as a result not of an actual innovation, but rather of a mistaken belief (self-fulfilling race dynamics). For instance, observers have argued that much of the proliferation of R&D in the United States in the early 1960s resulted from misperceiving Russian successes.

The second assumption is that each nation behaves as if its intensity of R&D effort does not influence R&D spending in its rivals. Although cross-nation interactions may be modeled in alternative ways, this assumption is a simple, useful benchmark in finite horizon games (it corresponds to the well-known Cournot competition) and may not lack empirical content.

Finally, let me say that my analysis abstracts from issues concerning the optimal menu of R&D activities, the trade-off between devoting resources to R&D rather than actual production of existing weapons (qualitative versus quantitative races), and issues of complementarities and substitutabilities. Attempting to account for these elements would dramatically complicate the present analysis. In any case, it may not be a major limitation, since the types of weapons I consider here are often perceived as not having any close substitutes.

The Dynamics of the Race

The race begins with the two nations in stage 0. It ends when both of them have developed the weapon or when one has dropped out while the other still continues. At each point in time, a nation has a relative and an absolute position in the race. It either leads, lags, or is tied with its rival; and it has either completed, is close to (has the intermediate result), or is far from (does not have the intermediate result) developing the weapon.

A nation tries to advance its position by spending on R&D, but the outcome is uncertain. If it succeeds, then it moves to the next stage. Otherwise, it repeats the current stage (if it chooses to remain in the race). I will postulate that the probability of success (that is, completion of the current stage) is a function of the amount spent

13. For example, see Brams and Kilgour 1988.

currently. I will also allow the relationship between spending and success to differ across nations (to capture differences in economic and technological status, quality of researchers, and so on) and to depend on one's absolute and relative position in the race. This is useful for modeling intertemporal spillover effects within the nation that successfully completes a stage (learning) or across nations (which will allow the modeling of imitation in a simple manner). A formal exposition of the structure of the model and the resulting dynamics of the race can be found in the appendix. In this section I offer a heuristic description of the decisions faced by the two rivals as they move through the various phases of the race.

There are six phases (see the appendix for a more detailed explanation):

1. Both nations have completed development (stage 22).[14]
2. One nation (the winner) has already completed the project, whereas the other one (the loser) only has the intermediate result (stage 21 for the winner and 12 for the loser).
3. Both nations have the intermediate breakthrough, but neither has completed development yet (stage 11).
4. One nation has completed the whole project, whereas the other has not even come up with the intermediate result (stage 02 for the loser and 20 for the winner).
5. One nation has the intermediate result, whereas the other has nothing (stage 10 for the leader and 01 for the laggard).
6. Neither nation has the intermediate result (stage 00).

To describe the behavior of a nation at any given point in the race, we must know the options the nation faces as well as their associated costs and benefits. A simple way of formally summarizing all this information is through the use of the value function, which simply computes the net benefits that accrue from pursuing development in a particular stage. For nation A, it takes the general form

$$
{}_AV_{ij} = -\,c_A({}_Ap_{ij},\ {}_AH_{ij}) + {}_AG_{ij} + {}_Ap_{ij}(1 - {}_Bp_{ij})\ {}_AV_{i+1,j}
$$

$$
+ (1 - {}_Ap_{ij})\ {}_Bp_{i,j+1}\ {}_AV_{i,j+1} + {}_Ap_{ij}\ {}_Bp_{ij}\ {}_AV_{i+1,j+1} + (1 - {}_Ap_{ij})(1 - {}_B{}_{ij}){}_AV_{ij}
$$

where ${}_AV_{ij}$ is the net benefit that nation A enjoys from being in stage *ij* and ${}_Ap_{ij}$ is the probability that nation A will complete stage *i* when its rival is in stage *j* if it spends an amount equal to $c_A({}_Ap_{ij},\ {}_AH_{ij})$. Note that the probability of success depends not only on the resources spent but also on the possibility of imitation (${}_AH_{ij}$).

According to this equation there are four possibilities:

14. Stage *ij* means that the nation under consideration is in stage *i,* and its rival is in stage j, where $i,j = 0, 1, 2$.

1. Nation A succeeds, but nation B fails. In this case the game moves to the stage $i + 1, j$ (from nation A's point of view). The likelihood of this event is simply ${}_{A}p_{ij}(1 - {}_{B}p_{ij})$, and nation A's expected value associated with this development is ${}_{A}V_{i+1,j}$.
2. Nation A fails, but nation B succeeds. In this case the game moves to stage $i, j + 1$. The likelihood of this event is simply $(1 - {}_{A}p_{ij})\ {}_{B}p_{i,j+1}$, and nation A's expected value associated with this development is ${}_{A}V_{i,j+1}$.
3. Both nations succeed (something that happens with probability ${}_{A}p_{ij}\ {}_{B}p_{ij}$. In this case the game moves to stage $i + 1, j + 1$, and nation A's valuation is ${}_{A}V_{i+1, j+1}$.
4. Neither nation succeeds (something that happens with probability $(1 - {}_{A}p_{ij})$ $(1 - {}_{B}p_{ij})$), in which case the status quo is maintained (${}_{A}V_{ij}$).

Finally, the term ${}_{A}G_{ij}$ represents the benefits (losses) that accrue within this period simply from having to spend this period in stage *ij*.

I now turn to a more detailed description of the various stages of the game. The last stage (stage 22) is of no interest from the point of view of racing, because both countries have completed the project. Let me then describe stage 12. In this stage, one nation has already developed the weapon (the winner), whereas the other (the loser) only has achieved the intermediate result. The former no longer needs to devote any R&D resources to this particular project. Moreover, as long as the laggard is still without the weapon, the winner enjoys an improvement in the distribution of power that translates into a per period benefit (payoff), K.[15] Although this benefit is eliminated when the loser catches up, a nation may still draw some benefits from possession of this weapon—say, $W > 0$—even if others have it too (perhaps because of deterrence reasons or because there are technological spillovers across different weapon systems). For the sake of generality, I will also allow for the possibility that a nation may be worse off when both nations have the weapon than when neither have it ($W < 0$). The loser must decide whether to concede the race and accept the new distribution of power or to try to catch up (and how much effort to expend in the process).

Staying in the race is costly because a nation must devote scarce economic resources to the development of the weapon. This direct cost of R&D depends, among other factors, on the intensity of effort, the quality of the human and other resources employed, and the availability of the appropriate intermediate goods. It may also depend on whether possession of the intermediate breakthrough makes research easier during the final stage of the project (intertemporal spillovers)—that is, whether success breeds success, possibly because of learning—and on the effectiveness of espionage activities that may provide solutions to some of the technical problems encountered in this stage (imitation).

15. For an example of this type of per period cost (the scenario of Russia reverting to communism and secretly developing a dominant ABM system), see Weinberger, Schweizer, and Thatcher 1998.

At the same time, dropping out is also costly for two reasons. First, the laggard nation suffers a loss in each and every period (denoted by R_2) as long as the distribution of power has worsened. Second, if the development of the weapon is of value to a nation independently of how far behind one finishes ($W > 0$), then dropping out means forgoing these benefits.

Consequently, the laggard selects a level of R&D spending that balances these costs and benefits. If R&D effort proves successful, both nations have the weapon and the race ends. If not, and the laggard decides to remain active, then the same process is repeated again.

Let me describe some of the properties of absolute R&D intensity during this phase. The assumption that the laggard nation suffers a per period loss as long as it has not caught up ($R_2 > 0$) has two important implications. First, a loser never concedes a race. Second, as losses cumulate with each failed attempt to catch up, a loser will try to restore the previous balance of power as soon as possible. This translates into a high level of R&D spending. Obviously, the higher the R_2, the higher the laggard nation's R&D spending.

Is unilateral withdrawal from the race a possibility in the absence of such recurrent losses? An incentive to remain in the race still exists even with $R_2 = 0$, as long as some benefit accrues to crossing the finish line independent of order (that is, when there is a direct reward from developing the weapon even if one is not the first to do so, $W > 0$). But in this case, there is no great urgency on the part of the laggard nation to complete development immediately, because losses are not cumulative. Unlike the earlier case (with $R_2 > 0$), which corresponds to a weapon that may be critical for the distribution of power, this case (with $R_2 = 0$ and $W > 0$) may correspond to a weapon that is developed for prestige or with the objective of being used as a possible future bargaining chip. Obviously, R&D intensity is increasing in W.

The preceding discussion concerning the specification of the gains and losses associated with the race highlights one key difference between my model and the standard patent race model.[16] Models of commercial R&D patent races often make a winner-takes-all assumption (in our model, this corresponds to setting $R_2 = W = 0$). This assumption implies that the race ends when one of the two competitors crosses the finish line, and it gives rise to dynamics that are different from those described in this article. For instance, it makes competition more intense when the contestants are even and has the leader outspending the follower.

The winner-takes-all assumption may be realistic for commercial races (because of patents or the possibility of undercutting competition through predatory pricing), but it does not seem to capture the incentives and actions observed in military technology races. In such races there are significant gains from catching up (or losses from failing to do so), so losers typically continue their development efforts. This is true even in situations where the reward from belated success is smaller than that of winning the race. For example, the development of the A-bomb and the H-bomb by the United States did not deter the Soviet Union from developing its own nuclear

16. Grossman and Shapiro 1987.

weapons. Similarly, the Soviet success in launching Sputnik and testing an intercontinental ballistic missile (ICBM) in 1957 stimulated rather than discouraged large U.S. programs in ballistic missiles and satellite technology and led in the long run to the initiation of such new weapon systems as MIRVs and strategic cruise missiles.

The other phases of the race can be analyzed similarly. At each point a nation must decide whether it will stay in the race and how much to spend on R&D, knowing (or having a perception of) where its opponent is in the race. It does so based on calculations of the benefits and losses associated with its relative and absolute position. I postulate that it is costly not only to lose the race but also to fall behind (because, for example, the bargaining position of the leader is strengthened or other nations switch alliances as a result of observing a technological advantage). I also allow for spying activities concerning the intermediate breakthrough; for leapfrogging, that is, getting the intermediate and the final results in one step; and for preemption,[17] that is, the lead nation using its advantage to prevent the laggard from persisting with its efforts. Naturally, the dynamics of the race are significantly affected by each of these possibilities.

The main findings are reported in the following section. My main objective is to characterize the intensity of the race (the amount spent on R&D) as a function of the two nations' absolute and relative positions in the race as well as of their other characteristics.

The Main Patterns

The model is too complex to be solved analytically, and so I have resorted to numerical solutions (see the appendix). Naturally, the solutions depend critically on the values of the parameters of the model, which in turn reflect the characteristics of both the weapon sought and the nations involved in the race. To avoid having to deal with a myriad of cases I focus on weapon systems and nations that have the following characteristics: (1) winning the race does not lead to a preemptive strike to prevent others from developing the weapon under consideration (because of political and/or military limitations); (2) the unilateral development of the weapon changes the distribution of power; and (3) nations are defense oriented—that is, they are more preoccupied with not losing rather than with winning a race (nevertheless, winning a race is always beneficial to the winner).

Table 1 is the benchmark case. The values selected for the benchmark case give this weapon the characteristics described earlier. The key feature is defense orientation. The per period loss from losing a race, R_2, is greater than the corresponding gain from winning a race, K. The benchmark case has two additional characteristics. First, a nation is better off having a weapon even when its rival also has it ($W > 0$; recall

17. Leapfrogging and preemption in the context of commercial patent races are analyzed in a multistage game by Fudenberg et al. 1983. For an extension of this model allowing for variable effort, see Grossman and Shapiro 1987; and Harris and Vickers 1987.

TABLE 1. *The benchmark case*

p12	*p02*	*p01*	*p10*	*p11*	*p00*
0.63	0.63	0.62	0.48	0.57	0.34

Note: $K = 1$, $W = 0.5$, $R_2 = 2$, $R_1 = 0.5$, $a = b = g = 1$, $h = 4$, $z = 3$, where
K = payoff to the winner of the race
W = payoff when both have developed the weapon
R_2 = per period loss to a laggard nation whose rival has completed development
R_1 = per period loss to a laggard nation whose rival possesses the intermediate result
b = spillovers from the intermediate to the final result within a nation
g = imitation of the intermediate result
a = imitation of the final result
h and z = parameters of the R&D cost function
$c(p_{ij}) = h(p_{ij})^z$
pij = effort level in stage *ij*

that W is the payoff when both have developed the weapon). Unilateral possession, of course, is even better ($K > W$). Second, even the intermediate breakthrough can induce a change in the distribution of power against the laggard, but it is not as bad as that resulting from unilateral full development ($R_1 < R_2$; R_1 denotes the loss suffered by the laggard when its rival only has the intermediate result).

Tables 2–8 show how particular parameters affect the intensity of R&D efforts during the various stages of the race. For instance, in Table 4 the parameter of interest is the damage suffered by the laggard nation when it finds itself in stage 12—that is, without the weapon—but its rival has already completed development (R_2). Two points are worth emphasizing. First, being behind is associated with more intensive R&D relative to being in the lead or in a position of parity (p12, p01, and p02 all identify stages in which the nation under consideration is lagging behind its rival; p10 represents a lead; and p00 and p11 represent positions of parity in the race). Second, increasing the cost of losing the race (from $R_2 = 1.5$ to $R_2 = 2.5$) intensifies effort and spending in all but the initial stage. For instance, the probability of success in stage 12 increases from.57 to .68, which requires that spending must increase by about 70 percent.[18]

In addition to these findings, there are several other interesting patterns. First, consider a weapon that offers an advantage to the winner as long as its rival does not possess it ($K > 0$) but has no value ($W = 0$) or even carries a deadweight loss ($W < 0$) if both have it. If the rewards and losses are fully understood from the beginning, this weapon may never be developed (p00 = 0 in Table 5). If for some reason a nation initiates the development of such a weapon (for example, if it miscalculates its

18. The cost of R&D is calculated by plugging the probability of success into the cost function. In this case, $c(0.57) = 4 \times (0.57)^3 = 0.74$ and $c(0.68) = 4 \times (0.68)^3 = 1.25$, a 69 percent increase. The cost function is described in the appendix. The parameter values are from the benchmark case.

TABLE 2. *The cost of R&D*

	p12	p02	p01	p10	p11	p00
$z = 4$	0.64	0.64	0.63	0.52	0.60	0.51
$z = 2$						0.00[a]

Note: z = parameter of the R&D cost function; $c(p_{ij}) = h(p_{ij})^z$; *pij* = effort level in stage *ij*.
[a]An entry of 0.00 indicates a number approximately equal to zero.

TABLE 3. *The laggard nation's loss when the leader only has the intermediate result*

	p12	p02	p01	p10	p11	p00
$R_1 = 0$	0.63	0.63	0.60	0.48	0.57	0.29
$R_1 = 0.8$	0.63	0.63	0.63	0.48	0.57	0.37

Note: R_1 = per period loss to a laggard nation whose rival possesses the intermediate result; *pij* = effort level in stage *ij*.

TABLE 4. *The laggard nation's loss when the leader has completed development*

	p12	p02	p01	p10	p11	p00
$R_2 = 1.5$	0.57	0.57	0.57	0.47	0.52	0.36
$R_2 = 2.5$	0.68	0.68	0.66	0.50	0.62	0.32

Note: R_2 = per period loss to a laggard nation whose rival possesses the final result; *pij* = effort level in stage *ij*.

rival's technical abilities), and if in addition its unilateral possession is important for the distribution of power, then the rival will have no choice but to follow suit.

Second, the intensity of R&D increases as the cost of resources used for military R&D decreases (Table 2). Moreover, if the cost of developing a particular weapon is excessive, then the two rivals may abstain from pursuing this weapon (in Table 2, p00 is 0.0000001 for $z = 2$).[19] The relative cost of R&D—in terms of consumption forgone—tends to decrease in a fast-growing economy. For the same reason, it is lower in more affluent societies. This tendency implies that nations such as China or India (who have grown fast relative not only to the United States but also to nations

19. Note that a higher "z" means a lower cost, because $p < 1$.

TABLE 5. *The reward when both have developed the weapon*

	p12	*p02*	*p01*	*p10*	*p11*	*p00*
$W = 1$	0.63	0.63	0.62	0.48	0.57	0.41
$W = 0$						0.00
$W = -1$						0.00

Note: W = payoff when both nations have developed the weapon; pij = effort level in stage ij.

TABLE 6. *The reward to the winner of the race*

	p12	*p02*	*p01*	*p10*	*p11*	*p00*
$K = 2$	0.63	0.63	0.63	0.55	0.59	0.45
$K = 0.8$	0.63	0.63	0.62	0.47	0.57	0.30

Note: K = payoff to the winner of the race; pij = effort level in stage ij.

TABLE 7. *Imitation of intermediate and final result*

	p12	*p02*	*p01*	*p10*	*p11*	*p00*
			Imitation of the intermediate result			
$g = 0.8$	0.63	0.68	0.67	0.48	0.57	0.28
$g = 0.6$	0.63	0.71	0.70	0.48	0.57	0.21
			Imitation of the final result			
$a = 0.8$	0.68	0.63	0.61	0.47	0.54	0.32
$a = 0.5$	0.79	0.63	0.60	0.44	0.49	0.29

Note: g = imitation of the intermediate result; a = imitation of the final result; pij = effort level in stage ij.

like Pakistan during the last thirty years) may have found military R&D spending more affordable and hence may have done more of it. If these high growth rates persist—as they are widely expected to—then the military R&D spending in these two nations is likely to increase significantly in the future.

Third, as the gains from winning the race (K) increase, so does the effort of those close to the finish line (whether they are in the lead or tied; see Table 6). Similarly, increasing the penalty for losing a race (R_2) intensifies effort throughout the race (Table 4). Finally, improving the effectiveness of espionage (lowering "a" and/or

TABLE 8. *Intertemporal, intranation spillovers (learning)*

	p12	*p02*	*p01*	*p10*	*p11*	*p00*
$b = 0.8$	0.68	0.63	0.64	0.54	0.70	0.38
$b = 0.6$	0.75	0.63	0.66	0.61	0.95	0.49

Note: b = spillovers from the intermediate to the final result within a nation; pij = effort level in stage ij.

"g") improves the prospects of success for the laggard nation and decreases its R&D spending. For instance, Table 7 suggests that if research on the intermediate breakthrough can be combined with espionage activities (say, "g" = 0.6), then the probability of developing the intermediate result for the laggard nation (p01) increases from 0.62 to 0.70, but the amount spent declines by about 25 percent ($4 \times 0.6 \times 0.7^3 - 4 \times 0.62^3$, see footnote 18).

One can use the findings reported in the tables to address several questions of interest concerning how relative and absolute positions in the race affect the intensity of R&D effort; for example,

1. Who devotes more resources to developing new technology: the nation leading the technological race or the one lagging behind? The technological laggard tends to devote significantly more resources to the development process than the leader; that is, p10 < p01 (recall that p_{ij} gives the probability of success—and hence the intensity of effort—when the county under consideration is in stage i while its rival is in stage j, where ij = 00, 01, 10, 02, 12, 11).

2. Starting from a position of parity at the beginning of the race, if a nation falls behind its competitor, does it increase its efforts in order to catch up, or does it get discouraged and lower R&D spending? Moreover, what happens to the intensity of the laggard's effort as the distance from the leader increases? Falling behind increases effort in order to catch up, that is, p01 > p00. Moreover, the intensity of the laggard's effort tends to increase somewhat as the distance from the leader increases, that is, p01 < p02.

3. If a nation that was ahead is caught up with from behind, does it intensify its effort in order to pull ahead again? An interesting way of restating this question is, is the rate of new weapons development higher when the two nations are competing neck to neck or when a nation develops the weapon from a position of technological advantage? A nation that is caught up with from behind accelerates spending, that is, p11 > p10. Moreover, the former laggard relaxes effort once it has restored parity, that is, p11 < p01. The total effect is that neck-to-neck competition is more intense.

4. If, from a position of parity, a nation moves ahead of its rival, does it increase effort or become complacent? If, starting from a position of parity, a nation

moves ahead of its rival, then it increases spending in order to take advantage of its lead, that is, p10 > p00.

5. Are R&D efforts higher when nations are close to completing their projects or when they are in the beginning of the race before any significant results have been achieved? In positions of parity, effort is lower in the beginning stages, that is p11 > p00.

Before concluding this section, let me briefly comment on the implications of including preemption in the model. Suppose that it is feasible—politically and militarily—for the winner of the race to use force to prevent its rivals from continuing with their efforts to develop the weapon under consideration (a preemptive strike such as those carried out by Israel). This means that the last phase of the race described earlier (stage 12 for the loser and 21 for the winner) is eliminated. This case corresponds to the winner-takes-all specification (where the race ends when one nation crosses the finish line) and gives rise to the standard dynamics found in commercial patent races described earlier. The laggard is now discouraged by the success of its rival. This is because the expected return to the laggard from persisting with intermediate-stage R&D is now lower because the leader is closer to the finish line and a preemptive strike—if the weapon is developed—will turn the laggard's investments to waste. This result means that a nation like Iraq may not try to develop nuclear weapons as vigorously as it would if it were not concerned about Israeli preemptive strikes (that is, the Israeli strategy of preemption may have discouraged nuclear development programs in the Middle East).

Finally, nothing in the model limits the number of nations participating in the race. Adding a third nation increases the number of possible configurations considerably but does not affect the qualitative results.

Empirical Aspects

The model has generated interesting predictions concerning the characteristics of military R&D races. Its main implication is that a nation will tend to spend considerably more when it lags behind or is tied with its rivals than when it leads. I now examine the empirical support for this proposition by studying two cases: The U.S.–Soviet technological rivalry and the recent Indian–Pakistani nuclear development programs. I conclude this section with a discussion of some additional predictions.

The U.S.–USSR Rivalry

The key pattern I examine regards how military R&D spending varies as a function of a nation's relative position in the race (the lack of relevant data poses a great hurdle to examining the other predictions). In particular, I ask whether weapons development programs in the United States accelerated as a result of U.S. perceptions of either falling behind or losing its technological lead and decelerated as a result of perceptions of surging ahead of the Soviet Union. In particular I focus on the U.S.–Soviet race to develop missile and ABM defense systems during the 1950s and 1960s.

I define the weapon under development as a combination of an offensive missile and an ABM system that gives a decisive strategic advantage to one of the two rivals, for instance, a system that makes a first strike a winning proposition. Obviously, this is a multistage development process, where generations of successive, individual missile and ABM systems represent intermediate steps that are valuable on their own (the R_1 term in equation (13) in the appendix). Moreover, unlike the model, where the end point is fixed (there is a known finish line), this race may have an uncertain ending point as the technological possibility frontier is pushed further out stochastically. The race ends when missile development can no longer contribute to military capabilities.

The close of World War II was marked by two significant technological developments: the nuclear bomb and ballistic missiles. These two innovations created the possibility of producing a major new weapon system, namely, the nuclear armed, intercontinental guided ballistic missile.

The United States initiated several programs aimed at missile development (the Snark, Navajo, and Redstone are some of the early missiles developed). These programs intensified significantly after 1952 (six new crash programs were initiated) mostly as a result of intelligence information that the Soviet Union had not only made progress in the development of large long-range rockets but also enjoyed a head start of several years in this area (a conclusion reached by the Von Neumann committee).[20] These efforts led to the development of missiles such as the Atlas, Titan, Minuteman, and Polaris.

In August 1957 the Russians launched a test ICBM that traveled the length of Siberia; and two months later, in October 1957, the first artificial satellite (Sputnik) went into orbit. These events sent shock waves throughout the rest of the world as they created the impression of a significant Soviet lead in missile development, the so-called missile gap. This gap consisted of a hundredfold weight gap between the first U.S. and Soviet satellites and a time gap in the launching of ICMBs (sixteen months) and first manned orbital flights (Gagarin's flight took place ten months before Glenn's).[21] How did funding for related R&D programs in the United States behave around the time of these two events? In the summer before Sputnik was launched, U.S. spending on ballistic missile research and space programs had been significantly curtailed. After Sputnik, Congress immediately passed a supplementary defense budget that restored reductions in the missiles programs and increased the budget of space programs beyond what it had been before the cuts.[22] A number of "exotic" missile-space projects were also funded (such as Dyna-Soar and the Aerospace Plane).

20. York 1970, 86.
21. Ibid., 109.
22. Ibid., 126.

As a result of new intelligence information confirming that the Russians were not enjoying a lead in missile deployment, many programs were phased out or cancelled late in the Eisenhower administration or very early in the Kennedy administration.[23] For instance, funding for the Aerospace Plane decreased from $200 million to $25 million and was discontinued in 1961 (Semi Automatic Ground Environment [SAGE] suffered a similar fate). But this lull did not last long. In 1961 the Soviet Union initiated deployment of an ABM system around Leningrad (in Griffon) and began a series of high-altitude nuclear tests (tests of existing ABM war heads and also tests aimed at developing a new X-ray–intensive ABM warhead). These activities led the United States to conclude that large ABM deployment was imminent.[24] U.S. fears were exacerbated in 1962 when another possible ABM site near Moscow was sighted (Khrushchev's statement in June 1962 that Soviet missiles could hit a fly in space may also have contributed to U.S. fears). The initiation of the MIRV programs was the direct consequence of these developments.

The picture changed again in early 1963 when it was discovered that the Leningrad ABMs were too slow and poorly maneuverable to be of any effectiveness against U.S. missiles (such as the Polaris A-3). At the same time, construction at the Moscow site seemed to have run into problems. These events led to a slowdown in U.S. MIRV development.[25] For example, the Polaris B-3 program was postponed for at least a year, and the Mark 12 program was delayed and nearly cancelled.

The pendulum swung in the other direction in late 1963 and early 1964 as a result of new intelligence findings indicating Soviet progress. New Soviet ABM sites were observed (in Tallin and elsewhere), old ones were upgraded with more advanced systems (Moscow), and tests of an improved high-altitude interceptor took place at Sary Shagan.[26] As a result, U.S. MIRV development accelerated dramatically during 1964 (for example, the Mark 12 programs were accelerated and reconfigured, the B-3 warhead was made bigger, and it was decided to develop MIRVed front ends for Poseidon and Minuteman missiles). The MIRV development "for the Poseidon programs started mainly because of the uncertainty of the Tallin threat."[27]

The rest of the decade continued in a similar fashion with one apparent exception. Intelligence information in 1967 suggesting that the sophistication of Soviet ABM systems fell short of prevailing perceptions did not lead to a slowdown in MIRV development in the United States. Although one may interpret this behavior as reflecting the influence of political and bureaucratic forces tied to an ongoing project, Ted Greenwood argues that it resulted partially from U.S. fears that the Soviets might introduce new, more advanced systems and partially from the fact that the Soviets were developing a new interceptor and upgrading their ABM radar.[28]

23. Ibid., 147.
24. Greenwood 1975, 97.
25. Greenwood 1975, 99.
26. See ibid.; and Weber 1991, 189.
27. Senate Committee on Armed Services 1968 (quoted by Weber 1991, 190).
28. Greenwood 1975, 102.

In conclusion, the MIRV seems to be "a prime example of an interactive, action–reaction process driving the nuclear arms race."[29] This pattern is precisely what the theory predicts.

It is worth noting that this pattern may not be easily accounted for by strong versions of some other theories of R&D spending that draw a sharp distinction between national and special group interests and emphasize solely the role of the latter (for example, theories of bureaucratic politics, the military industrial complex, and technological momentum). This inability is because these theories tend to predict that R&D spending follows mostly its own course and is relatively unresponsive to developments in rival nations (at least when reductions are necessitated as a result of establishing a clear lead over the competitors). The empirical evidence, though, seems to refute the thesis that the dynamics of weapons development programs are unrelated to perceptions of national interest. By "national interest" here I mean the value of the game for the nation in each phase as described in the appendix.

The Indian–Pakistani Nuclear Development Programs

I now turn to an important recent development, namely, the nuclear tests conducted by India (May 1998). It may appear that the most plausible rationalization for these tests is their possible political benefits for the ruling party in India. Can my model account for this situation? The model predicts that a nation accelerates significantly the process of weapons development when either (1) it loses its technological lead, or (2) it finds itself lagging behind its rivals. Moreover, the latter condition is associated with the greatest intensification. If one takes these tests to be part of the Indian–Pakistani race, the model fails to justify them, since neither the first condition nor the second seem to have occurred recently. This is not the case, though, if one views the tests as part of the Indian–Chinese race (where India has a significant lag) rather than the Indian–Pakistani race (where the rivals seem to be more or less in a position of parity or perhaps India enjoys a slight lead). According to the *Wall Street Journal*, "China has always been the focus of India's nuclear program. . . . The Indian Prime Minister Atal Bihari Vajoayee made clear that long-unspoken truth in his letter to U.S. President Bill Clinton and other world leaders explaining why India conducted the initial, triple test. China got top billing, though he did not mention it by name."[30] If this is true (and my model actually validates this interpretation), then Southeastern Asia is likely to experience a major military technology race in the future, with China being the driving force behind it. As China becomes wealthier, it is likely to try to challenge the United States' military hegemony. Being the technological laggard vis-à-vis the United States, China will have to increase R&D spending significantly (and hence the rate of its weapons development). But this will tend to increase China's lead over India, making India redouble its efforts to prevent this from happening. Undoubtedly, Pakistan will be forced to follow suit to prevent India from surging ahead.

29. Greenwood 1975, 104.
30. "Fear of China Drives India Tests," *The Wall Street Journal*, 15 May 1998, 1.

This interpretation is also consistent with India's (and hence Pakistan's) refusal to sign the nonproliferation treaty, suggesting that the heart of the problem may be that India lags behind China technologically rather than Indian–Pakistani distrust and insurmountable monitoring difficulties.

Additional Empirical Observations

Some of the other questions posed in the introduction can be addressed in a similar fashion. For instance, the model predicts that reducing Israel's technological lead will increase Israeli R&D spending significantly and decrease somewhat the intensity of effort by Israel's rivals. If one identifies the rate of introduction of new weapons with p10 and p11 (the probability that a nation will develop the weapon), then the net effect will be that the pace of introduction of new weapons in the Middle East will accelerate. To see this, consider the benchmark case (Table 1). Israel being in the lead translates into a probability of introducing a new weapon of 0.48 (p10). A tied race, though, is associated with a probability of 0.57 (p11), a 20 percent increase.

The question of whether military R&D programs will accelerate when China challenges the United States has an affirmative answer, since the theory predicts that a competing laggard spends a lot and a challenged leader accelerates significantly.

I conclude this section by describing another possible use of my model. In the introduction I argued that there has been a large increase in the share of post–World War II defense budgets devoted to R&D. Although the model is not designed to account for this pattern directly (the model contains no other types of military spending, so spending shares cannot be calculated), it can offer some indirect insights concerning the factors behind the large increase in the level of spending.

The model predicts that R&D intensity will increase if the rate of return to R&D becomes high, that is, if the perceived payoffs from leading or winning (or the losses from falling behind in) a major race go up (Table 6). The payoffs associated with the weapons pursued/developed in the post–World War II period may indeed have this characteristic since they have the potential to bring about significant changes in the distribution of power. The nuclear bomb, MIRVS, ABM, and SDI systems all had the property that a unilateral, successful development could allow a nation to dominate world military affairs.

It must be noted that commercial technologies—which often represent spin-off military technologies—have had very high rates of "return" (measured in financial terms, market shares, and so on) from the 1950s through the early 1970s. The main reason for these high rates of return (and hence for the desirability of R&D) may be found in the plethora of important advances that took place during World War II and that made additional innovations easier to generate (that is, they increased the productivity of R&D activities). This effect is captured in my model by the parameter "b" (see equation (1) in the appendix). A decrease in "b" leads to higher R&D intensity and spending. In addition, the frequency and extent of technological breakthroughs in the early post–World War II period also implies that the two super powers found themselves in the intensive R&D stages 11, 10, 01 rather than in the less intensive stage 00.

Note that the share of military R&D in defense spending has stabilized over the last twenty-five years (with the exception of the early 1980s). This may partly reflect the realization that additional major innovations may not be feasible. According to Herbert F. York, it has become "harder to invent anything that can make a real difference."[31] A similar pattern has been observed in commercial R&D and has been blamed for the post-1974 slowdown in productivity in the United States and other industrialized nations.

Conclusions

Political science is becoming increasingly interested in constructing models that can be used to forecast important political phenomena. In this article I have built a rigorous, quantitative framework that may prove useful for explaining the dynamics observed in interstate military technological rivalries. Admittedly, the model is stylized. Nonetheless, it produces clear predictions regarding the intensity of effort (the use of resources) in the nations participating in a technological race. For weapons that are critical for the distribution of power (but cannot be used in a preemptive strike), the typical pattern involves a great effort to close a technological gap, relative complacency when one has the lead, and an intense race in conditions of parity when the nations are close to developing the weapon.

The predicted patterns seem empirically plausible. They are consistent with the U.S.–Soviet missile race in the 1950s and 1960s and the recent conduct of nuclear tests by India. Nevertheless, many important tasks remain. It would be interesting to attempt to introduce multiple, interrelated research projects and to rank and correlate them in terms of "insurance" and national security. It may also be interesting to consider other forms of strategic interaction (for instance, to allow for signaling and manipulation) as well as diverse national objectives that may differ across nations. The methodology developed in this article seems quite promising and versatile for addressing military technology issues that play a central role in the design of modern defense policy and are likely to prove critical for the distribution of international power. It can also be used to address issues surrounding arms control agreements.[32]

Appendix

Formal Description of the Race

Assumptions

1. The race has two participants (nations or coalitions of nations), A and B, that compete for the development of a new weapon system. Decisions concerning the development of new weapon systems are reached by a single leader.[33]

31. York 1970, 165.
32. Koubi 1998.
33. For a justification of the unitary actor assumption, see Bueno de Mesquita 1981; and Bueno de Mesquita and Lalman 1992.

2. Technological competition is centered on a single project (weapon).
3. The race has three stages. Success during the first stage of R&D produces an intermediate result that may have some value on its own (perhaps 0) and is also a prerequisite for success in the second stage of R&D. Allowing for leap-frogging is technically feasible, and I describe how it can be incorporated into the analysis. Nonetheless, I believe that one usually has to take several steps in succession by solving a number of intermediate problems before the final stage can be completed. For example, various technological problems in aerodynamics, propulsion, electronic control, and explosive yield had to be solved before effective, unmanned long-range ballistic missiles could be developed.
4. The two participants behave according to the standard Cournot model.
5. Imitation (partial or full) of the intermediate and/or the final result may be possible.
6. There is an advantage to winning the race, but losing is also rewarded if the loser persists and manages to develop the weapon.
7. A nation can achieve a probability of success in period t, p_t, if it spends an amount equal to $c(p_t)$, where $c(0) = 0$, $c'(p) > 0$, and $c(p)$ is strictly convex.

I focus attention on a subgame perfect Nash equilibrium. In each period t, each side observes the opponent's position and then chooses its investment in R&D based on that observation. I compute the optimal choice of effort as well as the expected value from R&D activities in each and every stage under all possible configurations for the positions of the two rivals. There are five possibilities: (1) neither nation has achieved the intermediate stage; (2) one nation has completed the intermediate stage but not the final stage, and the other nation has not achieved the intermediate stage; (3) both nations have achieved the intermediate stage but not the final stage; (4) one nation has achieved the final stage and the other the intermediate; and (5) one nation has achieved the final stage, and the other has not yet completed the intermediate stage. I will use the subscripts i and j ($i = 0, 1, 2$; $j = 0, 1, 2$) to denote the phase of the race (0 for the initial stage, 1 for the intermediate, and 2 for the final result). For instance, $ij = 10$ means that the nation under consideration has achieved the intermediate stage, and its rival has not; $ij = 02$ means that the nation under consideration is still in the initial stage, but its rival has completed the project; and so on. Subsequently, ${}_{A}p_{11}$ denotes the probability that nation A will complete the project when both A and B have already achieved the intermediate result; ${}_{B}p_{01}$ denotes the probability that nation B will achieve the intermediate result when this stage has already been achieved by its rival (nation A), and so on. Similarly, I use $sVij$ ($s =$ A, B) to denote the value of the game to nation s in stage ij. Each nation is assumed to select a level of effort that maximizes its value function, taking as given the behavior of its rival.

I will carry out the analysis in a recursive manner, starting from the most advanced stage, $ij = 12$, when one nation has already developed the weapon (say, nation B) and the other only possesses the intermediate result (say, nation A). If in period t, nation A chooses to finance an R&D intensity of ${}_{A}p_{12}$, then the value of the game for nation A,

${}_{\mathrm{A}}V_{12}$, as a function of current and future optimal actions, is defined as follows:

$$ {}_{\mathrm{A}}V_{12} = -a_{\mathrm{A}} b_{A}\, c_{\mathrm{A}}({}_{\mathrm{A}}p_{12}) - {}_{\mathrm{A}}R_2 + {}_{\mathrm{A}}p_{12} W_{\mathrm{A}} + (1 - {}_{\mathrm{A}}p_{12})\, {}_{\mathrm{A}}V_{12} \qquad (1) $$

where $1_{\mathrm{A}}\mathrm{V}_{12}$ is the value the nation places on participating in the current phase of the race, and ${}_{\mathrm{A}}\mathrm{p}_{12}$ is the probability that this period's efforts will be met with success (nation A will end up with the desired weapon).[34] The first term on the right-hand side of equation (1) is nation A's current direct cost of R&D. The second term, ${}_{\mathrm{A}}\mathrm{R}_2$, represents the loss suffered by nation A as long as the balance of technological power remains tilted in favor of nation B. The third term, W_{A}, captures the benefit from catching up with a successful rival and thus restoring the distribution of power. The fourth term corresponds to current failure to catch up—an event that occurs with probability $1 - {}_{\mathrm{A}}p_{12}$—and is simply the status quo.

The parameters "b" and "a" will be used to capture spillover effects either across stages for the same nation (learning) or across nations (imitation). The value of "b" ($0 < b < 1$) will measure the positive effects that successful intermediate-stage research has on the effectiveness of final-stage research (a value of "b" less than unity implies that success breeds success, possibly because of learning). I will use "a" ($0 < a < 1$), on the other hand, to capture the opportunity for imitating the final result (similar opportunities will also be available for copying the intermediate result). If "a" $= 0$, then the weapon can be imitated at zero cost, whereas "a" $= 1$ leaves no room for imitation. I will also allow for imitation opportunities of the final result to differ from those of the intermediate one.

Note that if ${}_{\mathrm{A}}R_2 > 0$, then nation A will never give up its pursuit of this particular weapon (because if it does, it will keep on suffering a penalty indefinitely). Moreover, the laggard nation wants to have this weapon as soon as possible in order to stop suffering this loss (one could set $R_2 = 0$ to model weapons of lesser importance that would allow a nation to drop out unilaterally). Similarly, an incentive to remain in the race exists even when ${}_{\mathrm{A}}R_2 = 0$ as long as $W_{\mathrm{A}} > 0$ (that is, when there is a direct reward from developing the weapon even if both have it). But since W_{A} is a lump sum, it does not induce any great urgency in the laggard nation's effort to complete this project (so ${}_{\mathrm{A}}R_2 = 0$ and $W_{\mathrm{A}} > 0$ may refer to a weapon that is developed for prestige or with the objective of being used as a possible future bargaining chip).

Solving equation (1) for ${}_{\mathrm{A}}V_{12}$ gives

$$ {}_{\mathrm{A}}V_{12} = \frac{-a_{\mathrm{A}} b_{\mathrm{A}}\, c_{\mathrm{A}}({}_{\mathrm{A}}p_{12}) - {}_{\mathrm{A}}R_2 + {}_{\mathrm{A}}p_{12}\, W_{\mathrm{A}}}{{}_{\mathrm{A}}p_{12}} \qquad (2) $$

The optimal choice of effort dictates setting $d_{\mathrm{A}}V_{12}/d_{\mathrm{A}}p_{12} = 0$ in equation (2), which, after some manipulation that makes use of the definition of ${}_{\mathrm{A}}V_{12}$ from equation (2),

34. In general, ${}_sV_{ij}$, $s = \mathrm{A, B}$, is the value that the nation attributes to staying in the race when it finds itself in stage i and its opponent is in stage j ($i, j = 0, 1, 2$).

gives

$$_{A}V_{12} = W_{A} - a_{A}b_{A}\,c'_{A}(_{A}p_{12}) \tag{3}$$

where c′ is the marginal cost. Combining equations (2) and (3) gives an equation in $_{A}p_{12}$, namely

$$_{A}R_{2} - a_{A}b_{A}\,c'_{A}(_{A}p_{12})\,_{A}p_{12} + \; a_{A}b_{A}\,c(_{A}p_{12}) = 0 \tag{4}$$

Equation (4) determines the optimal choice of effort, $_{A}p_{12}$. Substituting this value into equation (3) gives the corresponding maximized value of the value function, $_{A}V_{12}$.

I now move back one step and calculate the optimal effort and the expected payoffs when both nations have achieved the intermediate (but not the final) result. If, in period *t*, nation A finances an R&D intensity of $_{A}p_{11}$, and nation B an intensity of $_{B}p_{11}$, then the value of the game for nation A, $_{A}V_{11}$, as a function of current and future optimal actions is defined as follows:

$$\begin{aligned} _{A}V_{11} = &- b_{A}c_{A}(_{A}p_{11}) + {_{A}p_{11}}(1 + {_{B}p_{11}})_{A}V_{21} \\ &+ (1 - {_{A}p_{11}})_{B}p_{11}\,{_{A}V_{12}} + {_{A}p_{11}}\,{_{B}p_{11}}W_{A} + (1 - {_{A}p_{11}})(1 - {_{B}p_{11}})_{A}V_{11} \end{aligned} \tag{5}$$

The first term on the right-hand side of equation (5) is nation A's current direct cost of R&D. There are four possible outcomes following the investment of $_{A}p_{11}$ and $_{B}p_{11}$ by nations A and B, respectively:

1. Nation A succeeds in developing the new weapon (an event that occurs with probability $_{A}p_{11}$) and at the same time nation B fails (an event that occurs with probability $1 - {_{B}p_{11}}$). Nation A then receives a payoff of $_{A}V_{21}$, and the expected value for nation A that is associated with this outcome is given by the second term of equation (5). $_{A}V_{21}$ is given by the following expression:

$$_{A}V_{21} = (1 - {_{B}p_{12}})K_{A} + {_{B}p_{12}}W_{A} + (1 - {_{B}p_{12}})\,_{A}V_{21} \tag{6}$$

where K_{A} is nation A's per period gain from having developed the weapon while nation B has not, and W_{A} is the benefit to nation A when both nations have completed the R&D process.

2. Nation A fails while nation B succeeds. The game then moves to the stage described earlier, where the payoff to nation A is $_{A}V_{12}$ (the third term).
3. Both nations succeed (the fourth term). The payoff to nation A is then W_{A}.
4. Both nations fail (the last term in equation (5)). The value of the game in the next period will be identical to that of the current period because the two rivals will find themselves in exactly the position in which they started out dur-

ing this period; that is, having achieved the intermediate result and still seeking the final one.

Solving equation (5) for ${}_{\mathrm{A}}V_{11}$ results in

$$ {}_{\mathrm{A}}V_{11} = \frac{-b_{\mathrm{A}} c_{\mathrm{A}}({}_{\mathrm{A}}p_{11}) + {}_{\mathrm{A}}p_{11}(1 - {}_{\mathrm{B}}p_{11}){}_{\mathrm{A}}V_{21} + (1 - {}_{\mathrm{A}}p_{11}){}_{\mathrm{B}}p_{11}\,{}_{\mathrm{A}}V_{12} + {}_{\mathrm{A}}p_{11}{}_{\mathrm{B}}p_{11}W_{\mathrm{A}}}{1 - (1 - {}_{\mathrm{A}}p_{11})(1 - {}_{\mathrm{B}}p_{11})} \quad (7) $$

Nation A chooses an effort level ${}_{\mathrm{A}}p_{11}$ in order to maximize equation (6), taking ${}_{\mathrm{B}}p_{11}$ as given. Taking the derivative of ${}_{\mathrm{A}}V_{11}$ in equation (7) with regard to ${}_{\mathrm{A}}p_{11}$, setting it equal to zero, and using the definition of ${}_{\mathrm{A}}V_{11}$ from equation (6) in the resulting expression gives

$$ {}_{\mathrm{A}}V_{11} = \frac{-b_{\mathrm{A}}\, c'_{\mathrm{A}}({}_{\mathrm{A}}p_{11}) + (1 - {}_{\mathrm{B}}p_{11}){}_{\mathrm{A}}V_{21} - {}_{\mathrm{B}}p_{11}\,{}_{\mathrm{A}}V_{12} + {}_{\mathrm{B}}p_{11}\,W_{\mathrm{A}}}{(1 - {}_{\mathrm{B}}p_{11})} \quad (8) $$

Combining equations (7) and (8) gives an equation in ${}_{\mathrm{A}}p_{11}$ and ${}_{\mathrm{B}}p_{11}$. Using the nation B counterpart to equations (7) and (8) produces another equation in ${}_{\mathrm{A}}p_{11}$ and ${}_{\mathrm{B}}p_{11}$. Solving these two equations simultaneously gives the optimal values of ${}_{\mathrm{A}}p_{11}$ and ${}_{\mathrm{B}}p_{11}$ (and substituting these values in equation (7)—or (8)—and in the corresponding equations for nation B gives the maximized value of ${}_{\mathrm{A}}V_{11}$ and ${}_{\mathrm{B}}V_{11}$).

I now move back one step and calculate the optimal effort and the expected payoffs when one nation has achieved the intermediate result but the other has not (the former nation is said to lead the technological race). The expected value of the game for the leader (say, nation A) is given by

$$ {}_{\mathrm{A}}V_{10} = -b_{\mathrm{A}}\, c_{\mathrm{A}}({}_{\mathrm{A}}p_{10}) + {}_{\mathrm{A}}p_{10}(1 - {}_{\mathrm{B}}p_{01})\,{}_{\mathrm{A}}V_{20} + {}_{\mathrm{A}}p_{10}\,{}_{\mathrm{B}}p_{01}\,{}_{\mathrm{A}}V_{21} $$
$$ + (1 - {}_{\mathrm{A}}p_{10})\,{}_{\mathrm{B}}p_{01}V_{11} + (1 - {}_{\mathrm{A}}p_{10})(1 - {}_{\mathrm{B}}p_{01})V_{10} \quad (9) $$

The first term on the right-hand side of equation (9) is the current cost flow. The second term is the leading nation's expected benefit if it moves further ahead of its rival, that is, if it completes the project (which happens with probability p_{10}) and its rival fails to come up with the intermediate result. Let us define its payoff in such a phase, V_{20}, as

$$ {}_{\mathrm{A}}V_{20} = K + {}_{\mathrm{B}}p_{01}\,{}_{\mathrm{A}}V_{21} + (1 - {}_{\mathrm{B}}p_{01})\,{}_{\mathrm{A}}V_{20} \quad (10) $$

The third term in equation (9) is the leading nation's benefit if it completes the project but at the same time its rival produces the intermediate result.

If, on the other hand, nation A fails (which happens with probability $1 - p_{10}$) and the laggard succeeds, then the race becomes a tie and the game moves to the next stage $ij = 11$, which was described earlier (the third term in equation (9)). Finally, if the leading nation fails to cross the finish line and the laggard does not achieve the intermediate result (which happens with probability $1 - p_{01}$), then the game in the next period starts from the same position (the last term in equation (9)). Solving equation (9) for ${}_{\text{A}}V_{10}$ gives

$$ {}_{\text{A}}V_{10} = \frac{-b_{\text{A}}\, c_{\text{A}}({}_{\text{A}}p_{10}) + {}_{\text{A}}p_{10}(1 - {}_{\text{B}}p_{01})_{\text{A}}V_{20} + {}_{\text{A}}p_{10}\, {}_{\text{B}}p_{01}\, {}_{\text{A}}V_{21} + (1 - {}_{\text{A}}p_{10})_{\text{B}}p_{01}\, {}_{\text{A}}V_{11}}{1 - (1 - {}_{\text{A}}p_{10})(1 - {}_{\text{B}}p_{01})} \tag{11} $$

The optimal choice of ${}_{\text{A}}p_{10}$ satisfies

$$ {}_{\text{A}}V_{10} = \frac{-b_{\text{A}}\, c'_{\text{A}}({}_{\text{A}}p_{10}) + (1 - {}_{\text{B}}p_{01})_{\text{A}}V_{20} + {}_{\text{B}}p_{01}\, {}_{\text{A}}V_{21} - {}_{\text{B}}p_{01}\, {}_{\text{A}}V_{11}}{(1 - {}_{\text{B}}p_{01})} \tag{12} $$

Equating equation (12) to equation (11) gives an equation in ${}_{\text{A}}p_{10}$ and ${}_{\text{B}}p_{01}$.

I now turn to the maximization problem faced by the laggard in the race (nation B). Its value function is described by equation (13):

$$ {}_{\text{B}}V_{01} = -g_{\text{B}}\, c_{\text{B}}({}_{\text{B}}p_{01}) - {}_{\text{B}}R_1 + {}_{\text{B}}p_{01}(1 - {}_{\text{A}}p_{10})_{\text{B}}V_{11} + {}_{\text{B}}p_{01}\, {}_{\text{A}}p_{10}\, {}_{\text{B}}V_{12} $$
$$ + (1 - {}_{\text{B}}p_{10})_{\text{A}}p_{10}\, {}_{\text{B}}V_{02} + (1 - {}_{\text{A}}p_{10})(1 - {}_{\text{B}}p_{01})_{\text{B}}V_{01} \tag{13} $$

The first term in equation (13) is the direct cost of R&D. The parameter "g" captures the opportunity for imitating (copying) the intermediate result (which is already available to the other nation). $g = 0$ implies costless imitation (that is, the result is achievable without the imitating nation doing any of its own R&D), and $g = 1$ implies no imitation at all. The second term in equation (13), R_1, measures the loss suffered by the laggard in the race. It is positive if the intermediate result can be used to influence the balance of power (for instance, if other nations switch allegiance toward the likely winner of the race). The third term describes the reward to the follower from catching up with the leader (by developing the intermediate result). The fourth term corresponds to success in both nations: The laggard gets the intermediate result, but at the same time the leader completes the project. The last term corresponds to the status quo (both nations fail in their respective projects); and the fifth term represents the worst possible scenario for the laggard, namely, its falling further behind the leader (the leader crosses the finish line, while the follower has yet to come up with the intermediate result). The value function in the last case is ${}_{\text{B}}V_{02}$ and will be derived shortly.

Solving equation (13) for V_{01} gives

$$ {}_{\mathrm{B}}V_{01} = \frac{-g_{\mathrm{B}}\, c_{\mathrm{B}}({}_{\mathrm{B}}p_{01}) - {}_{\mathrm{B}}R_1 + {}_{\mathrm{B}}p_{01}\, {}_{\mathrm{A}}p_{10}\, {}_{\mathrm{B}}V_{12} + {}_{\mathrm{B}}p_{01}(1 - {}_{\mathrm{A}}p_{10})\, {}_{\mathrm{B}}V_{11} + (1 - {}_{\mathrm{B}}p_{01})\, {}_{\mathrm{A}}p_{10}\, {}_{\mathrm{B}}V_{02}}{1 - (1 - {}_{\mathrm{A}}p_{10})(1 - {}_{\mathrm{B}}p_{01})} \tag{14} $$

Taking the derivative of ${}_{\mathrm{B}}V_{01}$ with regard to ${}_{\mathrm{B}}p_{01}$ and setting it equal to zero produces

$$ {}_{\mathrm{B}}V_{01} = \frac{-g_{\mathrm{B}}\, c'_{\mathrm{B}}({}_{\mathrm{B}}p_{01}) + {}_{\mathrm{A}}p_{10}\, {}_{\mathrm{B}}V_{12} + (1 - {}_{\mathrm{A}}p_{10})\, {}_{\mathrm{B}}V_{11} - {}_{\mathrm{A}}p_{10}\, {}_{\mathrm{B}}V_{02}}{(1 - {}_{\mathrm{A}}p_{10})} \tag{15} $$

Combining equations (14) and (15) results in another equation in ${}_{\mathrm{A}}p_{10}$ and ${}_{\mathrm{B}}p_{01}$. This equation together with the one derived by combining equations (11) and (12) can be solved for the optimal values of ${}_{\mathrm{A}}p_{10}$ and ${}_{\mathrm{B}}p_{01}$ (which can then be used to derive the corresponding values of V_{10} and V_{01}).

I now describe the optimization problem faced by a nation (say, B) that has fallen two steps behind its rival. Its value function is

$$ {}_{\mathrm{B}}V_{02} = -g^{*}_{\mathrm{B}}\, c_{\mathrm{B}}({}_{\mathrm{B}}p_{02}) - {}_{\mathrm{B}}R^{*}_{2} + (1 - {}_{\mathrm{B}}p_{20})\, {}_{\mathrm{B}}V_{02} - {}_{\mathrm{B}}p_{02}\, {}_{\mathrm{B}}V_{12} \tag{16} $$

The imitation coefficient, g^{*}_{B}, may now be different from that in the $ij = 01$ case, because the imitation set is different (both the intermediate and the final result are now available in nation A). Similarly, the loss associated with the change in the balance of technological power, R^{*}_{2}, may be different from that arising when the follower has the intermediate result (R_2). Solving equation (16) gives

$$ {}_{\mathrm{B}}V_{02} = \frac{-g^{*}_{\mathrm{B}}\, c_{\mathrm{B}}({}_{\mathrm{B}}p_{02}) - {}_{\mathrm{B}}R^{*}_{2} + {}_{\mathrm{B}}p_{02}\, {}_{\mathrm{B}}V_{12}}{{}_{\mathrm{B}}p_{02}} \tag{17} $$

And setting the derivative of ${}_{\mathrm{B}}V_{02}$ with regard to ${}_{\mathrm{B}}p_{02}$ equal to zero

$$ {}_{\mathrm{B}}V_{02} = -g^{*}_{\mathrm{B}}\, c'_{\mathrm{B}}({}_{\mathrm{B}}p_{02}) + {}_{\mathrm{B}}V_{12} \tag{18} $$

The optimal level of effort of nation B is found by combining equations (17) and (18).

Turning now to the initial phase of the race ($ij = 00$) and using the same methods applied earlier, we find that the value function of nation A is

$$ {}_{\mathrm{A}}V_{00} = \frac{-c_{\mathrm{B}}({}_{\mathrm{A}}p_{00}) + {}_{\mathrm{A}}p_{00}(1 - {}_{\mathrm{B}}p_{00})\, {}_{\mathrm{A}}V_{10} + {}_{\mathrm{A}}p_{00}\, {}_{\mathrm{B}}p_{00}\, {}_{\mathrm{A}}V_{11} + (1 - {}_{\mathrm{A}}p_{00})\, {}_{\mathrm{B}}p_{00}\, V_{01}}{1 - (1 - {}_{\mathrm{A}}p_{00})(1 - {}_{\mathrm{B}}p_{00})} \tag{19} $$

and that the optimal choice of ${}_{\mathrm{A}}p_{00}$ satisfies

$$ {}_{\mathrm{A}}V_{00} = \frac{-c_{\mathrm{A}}'({}_{\mathrm{A}}p_{00}) + (1 - {}_{\mathrm{B}}p_{00})\,{}_{\mathrm{A}}V_{10} + {}_{\mathrm{B}}p_{00}\,{}_{\mathrm{A}}V_{11} - {}_{\mathrm{B}}p_{00}\,{}_{\mathrm{A}}V_{01}}{(1 - {}_{\mathrm{B}}p_{00})} \tag{20} $$

Equations (1)–(20), together with their nation B counterparts, determine ${}_{\mathrm{A}}p_{00}$, ${}_{\mathrm{A}}V_{00}$, ${}_{\mathrm{B}}p_{00}$, ${}_{\mathrm{B}}V_{00}$.

The complete solution of the model is described by equations (1)–(20). These equations are nonlinear, which makes the derivation of analytical solutions not feasible. Although some comparative statics can be carried out even without analytical solutions, many important questions require knowledge of the levels of effort in the various stages of the race rather than just the direction of change. Consequently, I have resorted to numerical methods. I have also relied on a symmetric equilibrium in order to focus more clearly on the role played by relative and absolute position rather than by asymmetries (results obtained in an asymmetric equilibrium are available on request). In such an equilibrium no nation subscript is needed, and moreover ${}_{\mathrm{B}}p_{21} = {}_{\mathrm{A}}p_{12} = p_{12}$.

Preemption

Suppose that a preemptive strike is feasible both politically and militarily; that is, it is feasible for the winner of the race to use force to prevent its rivals from continuing on with their efforts to develop the weapon under consideration. This case can be studied adequately within the present framework by choosing the appropriate parameter values. An effective preemptive strike could be modeled by eliminating stage $ij = 12$; that is, by assuming that once a single nation has developed the weapon the race ends.

Leapfrogging

Such a possibility can be easily incorporated into the analysis by allowing R&D in the beginning of the race ($ij = 00$) to be associated with a positive probability, q, of generating the final result. Nation A then can achieve the final result with probability q_{A}; the intermediate result with probability $(1 - q_{\mathrm{A}})\ {}_{\mathrm{A}}p_{00}$; and neither with probability $(1 - q_{\mathrm{A}})(1 - {}_{\mathrm{A}}p_{00})$. The corresponding probabilities for nation B are q_{B}, $(1 - q_{\mathrm{B}})_{\mathrm{B}}p_{00}$ and $(1 - q_{\mathrm{B}})(1 - p_{00})$, respectively. Subsequently, equation (19) takes the form

$$ \begin{aligned} {}_{\mathrm{A}}V_{00} = &-c_{\mathrm{A}}({}_{\mathrm{A}}p_{00}) + q_{\mathrm{A}}[q_{\mathrm{B}}K^{*} + (1 - q_{\mathrm{B}})_{\mathrm{B}}p_{00}K + (1 - q_{\mathrm{B}})(1 - {}_{\mathrm{B}}p_{00})K] \\ &+ (1 - q_{\mathrm{A}})\,{}_{\mathrm{A}}p_{00}[q_{\mathrm{B}}\,{}_{\mathrm{A}}V_{12} + (1 - q_{\mathrm{B}})\,{}_{\mathrm{B}}p_{00}\,{}_{\mathrm{A}}V_{11} + (1 - q_{\mathrm{B}})(1 - {}_{\mathrm{B}}p_{00})\,{}_{\mathrm{A}}V_{10}] \\ &+ (1 - q_{\mathrm{A}})(1 - {}_{\mathrm{A}}p_{00})[q_{\mathrm{B}}\,{}_{\mathrm{A}}V_{02} + (1 - q_{B})_{B}p_{00\,A}V_{01} + (1 - q_{\mathrm{B}})(1 - {}_{\mathrm{B}}p_{00})\,{}_{\mathrm{A}}V_{00}] \end{aligned} \tag{21} $$

Equation (20) can be used to study how the possibility of leapfrogging affects the dynamics of the race (for arbitrary values of q).

Numerical Solution

To solve the model numerically, one must first parameterize it. The model contains several parameters: the cost function, c; the rewards attained from the completion of the R&D process (K, W); the losses that result from unfavorable developments in the balance of technological power (R_1, R_2 and R_2^*); imitation opportunities ($a, g,$ and g^*); and learning, b.

Unfortunately, nothing in the literature can help us to select realistic parameter values (that is, to calibrate the model). Although some degree of arbitrariness is inevitable, some choices are restricted not only by technological considerations (for instance "a" must be between zero and unity) but also by the fundamental characteristics of the technological race under consideration. For instance, consider the type of weapon sought. If the weapon is such that it does not matter in the long run who develops it first, as long as both nations develop it, then K and W ought to be comparable in size. A good example is the nuclear bomb (in the absence of a preemptive strike), which gave the United States only a temporary advantage. On the other hand, if the first introduction of a new weapon can permanently change the balance of power so that the winner's advantage is not eroded by the laggard's success, then the benefits to the winner of the race must be set to exceed considerably the benefits from belated success (K is large relative to W). Similarly, if nations mostly care about not losing a race rather than winning one (defense orientation), then R_2 ought to be larger than K. If nations are worse off when both have the weapon than when both have it, then $W < 0$. In a similar vein, one can argue that the loss suffered by the laggard nation as a result of its rival's development of the intermediate result is likely to fall short of that suffered when its rival achieves full development of the weapon ($R_2 > R_1$).

I assume that the cost function takes the form $c_s({}_sp_{ij}) = h_s\,({}_sp_{ij})^z$, $s = \text{A, B}$, $i = 0, 1$, $j = 0, 1, 2$, $h > 0$, $z > 1$ (convexity). Given a set of values for the parameters of the model, say G_1, the model was solved numerically in a recursive manner as follows:[35] I started with stage $ij = 12$. Equation (4) was used to determine the optimal value of ${}_Ap_{12}$ (and nation B's counterpart for ${}_Bp_{12}$). That value was then used in equation (3) to compute ${}_AV_{12}$ (and ${}_BV_{12}$ was calculated similarly). I then moved one step back to stage $ij = 11$ and used equations (7) and (8) as well as their nation B counterparts—together with the value already computed from the previous step value of ${}_AV_{12}$ and ${}_BV_{12}$—in order to calculate ${}_Ap_{11}$, ${}_Bp_{11}$, ${}_AV_{11}$, and ${}_BV_{11}$. I then used the computed values in the calculation of the optimal values of p and V in stage $ij = 02$. I continued in a similar fashion with $ij = 01$, $ij = 10$, and $ij = 00$ until the complete time series of

35. The numerical analysis was carried out using MATHEMATICA. The program is available from the author on request.

$_{s}p_{ij}(G_1)$ was computed. I then repeated the process using a different configuration of parameters, G_n, $n = 2, 3$.

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