Going Nuclear

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Abstract

The prominence of several "big picture" issues—such as global warming, energy security, and an energy economy—has meant that countries are beginning to seriously consider adopting nuclear technology as a source for energy. This trend has implications with regard to the proliferation of nuclear weapons, especially in places such as the Middle East and the Korean Peninsula. This paper aims to develop a model of country decisionmaking that takes into account the game-theoretic considerations involved in the production of weapons versus energy, especially in the presence of a player that has already acquired weapons. It finds that, while economic considerations can potentially offset the desire to acquire nuclear weapons acquisition, the presence of a nuclear-armed neighbor will lead to a race-to-the-bottom outcome where countries find it in their interest to proliferate. Policy implications of the analysis are also considered.

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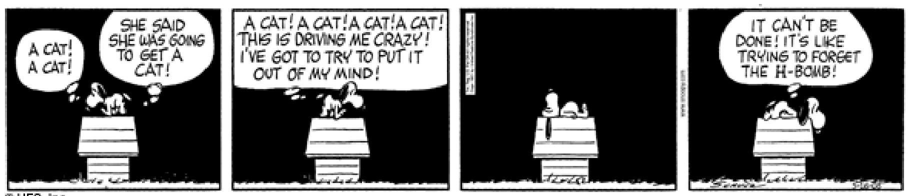

1 Introduction

The "big picture" issues that have dominated headlines in recent times—the anthropomorphic nature of global warming, the need for energy security amidst unstable suppliers of fossil fuels, and an increased desire to make clean energy the next major driver of economic growth—has meant that countries all over the world are beginning to seriously consider the transition from older energy producing technologies such as coal and oil toward nuclear power. Such a trend has implications for international peace, especially with regard to the possible proliferation of nuclear weapons.

Nowhere is this more evident than in the modern Middle East and the Korean Peninsula. The presence of one (more or less) known nuclear power (Israel and North Korea, respectively), together with the complex dynamics of political relationships in the region, has meant that country after country is making a bid to join the nuclear club. Moreover, growing demand for nuclear power—in response to both urbanization pressures as well as the potential for desalinized water as a desired byproduct—has meant that nuclear activities in the Middle East and East Asia have expanded significantly in recent years. This naturally raises the question of the extent to which such pursuits may affect the broader nonproliferation agenda.

The objective of this paper is to develop a very simple formal model of country decisionmaking over the production of nuclear weapons versus energy, taking into account the political-economic costs and benefits of this choice. In addition to the individual costs and benefits inherent in their optimization program, agents also consider interaction effects in their decisions. Importantly, the model considers how such choices may be altered by the introduction of a player that possesses nuclear weapons. The goal is to characterize the conditions under which countries may choose to forgo the production of weapons. In addition, we seek to explore how the introduction of a third player that has already acquired such weapons changes the complexion of the decisionmaking process for the remaining countries.

Our model highlights the deleterious effect that the possession of nuclear weapons by a third player has on the political-economic calculus of the remaining two parties. We find that, in the absence of such a player, the decision not to go down the nuclear path is remarkably stable, even if these countries possess nuclear power plants. This is because countries recognize the tradeoff between the production of nuclear weapons—which do not provide inherent economic gains—against the benefits of producing nuclear power, which yields positive externalities due to complementarities in its production and that of other economic goods. Surprisingly, this is the case even when we model one of the countries as a belligerent one (with the other choosing to acquire weapons only for the purposes of self-defense).

The story changes, however, when we allow the entry of a third player that already possesses nukes. In this case, the likelihood that the entire neighborhood goes nuclear rises dramatically, and countries in effect pursue a race to the bottom (since everyone would be made better off, economically speaking, in the absence of any weapons). Such an outcome would result as long as the costs of nuclear war—whether real or imagined—are sufficiently large. This result highlights the inherent instability of a nuclear presence in a given region, especially when it is perceived that the nuclear nation is able and willing to deploy its arsenal.

The formal literature on nuclear deterrence and proliferation has focused on primarily strategic considerations. For example, Powell (1988) deploys a model of sequential bargaining to examine how nuclear brinksmanship can serve to promote deterrence goals in the presence of two-sided incomplete information, while Powell (2003) introduces an institutional wrinkle—national missile defense—into a similar brinksmanship contest and examines its implications on equilibrium stability.

Formal work on arms races have similarly tended to focus on purely security considerations. For example, Kydd (1997) models a balance between players that are greedy (for power) and hungry (for security), and is able to find equilibria where these complex strategic interactions leads to spirals of reactionary military buildup. Moreover, to the extent that the guns-versus-butter tradeoff is captured, the literature has concentrated on resource allocation problems that typically treat nonmilitary expenditures as residuals to the arming decision (Brito & Intriligator 1985; Powell 1993).

Moreover, the problem of an armed player in the Middle Eastern neighborhood, while extensively debated and studied by the security community (IISS 2008), has not been examined in the context of a politico-economic rationalist framework. Similarly, while studies on nonproliferation in East Asia have begun to examine the consequences of North Korea's recent spate of nuclear testing (Haggard & Noland 2009), the analysis has generally been informal in nature. This gap has very real consequences. Understanding the (broadly-defined) rational motivations that drive the remaining actors in a nuclear neighborhood can help us clarify the channels by which countries choose to engage in weapons acquisition, and can inform (currently) non-nuclear neighborhoods about the potential consequences of a given member country going nuclear.

The rest of the paper is organized as follows. Following this introduction, we lay out the basic analytical framework of the model (Section 2), as well as the main propositions that derive from this framework. This is followed by a consideration of the policy implications of the previous section (Section 3), before a final section concludes with a recapitulation of the main messages. A technical appendix provides more detailed derivations of the propositions made in Section 2.

2 Analysis

Our analysis is premised on a setting comprised of two hypothetical countries, a pacifist and an antagonist, each which has a choice of producing either nuclear weapons or nuclear power,[1] along with the production of other, economically-relevant, goods. The pacifist nation will only use weapons in self-defense, while the antagonist nation has an incentive to acquire weapons for the purpose of belligerent activity. Although such asymmetry is by no means assured, it is not an uncommon circumstance in many regional environments; consider, for example, the cases of both European and Pacific theaters during the Second World War, the bulk of Arab-Israeli wars between 1948–2006, and the first Gulf War, where there has often been one clear aggressor.

A crucial assumption that we make is that the technology underlying each nation's aggregate output is such that, if it chooses to produce energy in conjunction with goods, the complementarities that arise from this combination leads to increasing returns to the production process, whereas a choice of weapons and goods are effectively substitutes, and hence subject to more traditional constant returns. This idea of increasing returns is usually justified by the presence of production externalities; we can think of how energy independence can spur greater incentives for manufacturing economywide, or how technological skills acquired by engineers and scientists in the energy sector spill over into the broader economy.

In rendering their choice between weapons or power, countries consider the opportunity costs of such a tradeoff: By choosing to produce energy, the pacifist nation gains the benefits of enhanced welfare from a greater capacity for national production, but forgoes its ability to deter the other nation from forcibly reducing its own output through a nuclear strike. Concomitantly, the antagonist nation can choose to weaponize and claim the prestige and leverage that accompany their nuclear status, but does so at the expense of forfeiting additions to its own national output.

A key parameter in our analysis is the extent to which losses are suffered by the peaceful country due to a nuclear strike as a result of belligerent action (what we term appropriation) or, alternatively, the extent of prestige and leverage that accrue to the warlike country when it is able to effect such a strike (what we

[1] Of course, it is entirely possible that a country can choose to produce *both* weapons and power. We believe that this is unlikely, for three reasons. First, the reprocessing of highly-enriched uranium or plutonium for weaponization generally requires the devotion of significant productive capacity, which would generally rule out any excess capacity for residual energy production in any given plant. Second, recent innovations in the design of proliferation-resistant reactors (Fahlen, Kim & Lyles 2007) has meant that it may be technologically impossible to extract spent fuel from such reactors for the purposes of weaponization. Third, global security arrangements prohibit the use of nuclear power plants as sources of weapons-grade material. For these reasons, the choice between usable energy and nuclear weapons is therefore effectively a choice between substitutes.

call aggression rents). We attempt to vary this parameter of interest—which we call ϕ—and ask how stable the nonproliferation outcome actually is. This combination of security and normative considerations have been identified by others (Sagan 1996–1997) as relevant to states' pursuit of nuclear weapons.

Given this setup, we solve for two types of equilibria in the model: One for a game that is played simultaneously, and the other for a game that has one country moving first, followed by the other. The solution concepts that we employ require that, in equilibrium, neither country has an incentive to deviate from its chosen strategy.

Our formal analysis (described in detail in the Appendix) arrives at two somewhat surprising results. First, we find that when countries give due consideration to both security and economic progress, it is usually possible to sustain a nonproliferation agenda, *even in our artificial setting where one nation is excessively bellicose*. This result is remarkably robust. In our numerical simulations—which make fairly modest assumptions about the underlying parameters of the model—even an implausibly large value of ϕ does not overturn the central result. Moreover, the central result holds—with minor quantitative differences that are inconsequential in a qualitative sense—regardless of whether both countries move simultaneously or sequentially. This finding supports the empirical observation that, in many regions of the world, there is relatively little pressure to acquire nuclear weapons.

Our second result allows a nuclear-armed third country to enter into the picture. While it is still possible to recover the nonproliferation result, the presence of a nuclear power in the neighborhood changes the conditions for which a proliferation outcome emerges (and the same condition obtains in either the simultaneous or sequential version of the game). Using the same parameter values as before, we find that there is a critical threshold for which both countries will now pursue nuclear weapons. Unfortunately, this threshold is not too difficult to breach. As long as the costs of nuclear war—whether real or imagined—are sufficiently large (a high ϕ), countries will choose the welfare-inferior but safer option of weaponizing (as a means of deterrent defense). The nuclear presence in a given region, therefore, is ultimately disruptive to regional efforts at supporting nonproliferation.

To be reasonable, our model needs to offer credible explanations for two observed phenomena: First, why has the ownership of nuclear weapons not destabilized the neighborhood around the five official nuclear weapons states, while recent aspirants to the nuclear club—notably North Korea and Iran—have increased pressures for weapons acquisition in their neighborhoods? Second, why have certain countries—such as South Africa and several states in the former Soviet Union—have been willing to voluntarily forgo their ownership of nukes?

The key difference that accounts for the first set of divergent outcomes appears to lie in the appropriation/aggression parameter ϕ. During the Cold War, ϕ was likely to be high. The Soviet Union acquired weapons in 1949 as a counterbalance to the other superpower of the time, the United States. The other nuclear weapons states are all in the same neighborhood: France and the

United Kingdom, China and Russia, India and Pakistan. The presence of a Soviet bomb undoubtedly influenced the decision for the U.K. and France to step up development efforts; the subcontinent's decision to go nuclear was preceded by continued Sino-Indian border disputes, the vulnerabilities exposed by India's 1962 war with China, and the traditional rivalries between India and Pakistan.[2]

After this initial drive, the value of ϕ in the neighborhood of the nuclear weapons states would have fallen. In part, this was due to nuclear deterrence (Zagare & Kilgour 2000)—which reduced the likelihood of actual nuclear weapons deployment in the event of war—but also because of the partial dissipation of ego rents associated with nuclear weapons possession, as economic strength became a more prominent measure of global influence. Moreover, three of the five nuclear weapons states are mature democracies, with very little incentive to use nuclear force against their immediate neighbors; Russia and China's strong economic ties with their regional neighbors have also strongly curbed on their taste for cross-border conflict—the so-called trade-promotes-peace hypothesis (Martin, Mayer & Thoenig 2008)[3].

Contrast this to a nuclear North Korea or Iran. Given their pariah status in the international system, and the belief that the leadership of these nations are able and willing to exercise the nuclear option, a bomb would lead to a high value of ϕ in these regions. As a consequence, pressure is increasing among regional neighbors in Northeast Asia and the Middle East to go down the nuclear road themselves.

As for the second question, one reason why Belarus, Kazakhstan, Libya, South Africa, and the Ukraine voluntarily gave up their nuclear weapons is because the opportunity costs of not doing so would have been too great. With little to gain from belligerent activity against their neighbors, choosing guns over butter would have imposed too severe a cost on their economies in terms of lost production. As a result, these countries simply chose to maximize national welfare, which in their cases lead to the stable, nonproliferation outcome.

Finally, while the analysis presented here captures the effect that a nuclear neighbor can have on a region, it is important to point out that the model is silent on what drives a given state's decision to acquire nuclear weapons in the first place, especially in the absence of nuclear neighbors. This is a question better answered by a careful analysis of potential determinants, and recent scholarship (Jo & Gartzke 2007; Singh & Way 2004) has made some early headway toward answering this question.

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[2]The decision to acquire weapons, of course, was multifaceted and complex, and we by no means wish to exclude other explanations behind the initial drive to acquire nuclear weapons. Nonetheless, we would argue that the presence of nuclear neighbors was a relevant factor all of these countries' choices.

[3]The pursuit for economic prosperity in East Asia, compared to the stagnancy of economies in the Middle East, could also play a role in mitigating the incentive to go nuclear. In terms of our model, East Asian countries are in a better position to exploit the increasing returns resulting from the production of energy and other economic goods. See (Solingen 2007).

3 Policy

The Nonproliferation Treaty (NPT) of 1968, which is the centerpiece of global nuclear nonproliferation efforts, is often seen as resting on three interrelated pillars: The principle of nonproliferation (among non-nuclear weapons states), the eventual disarmament (among nuclear weapons states), and the sovereign right of nations to use nuclear technology for peaceful purposes.

Most enforcement mechanisms for nonproliferation have, for good reason, focused on the first and second pillars. The monitoring of nonproliferation has generally looked to either technological or political solutions. The most significant among the technologically-based approaches are the global safeguards imposed by the International Atomic Energy Agency (IAEA), especially the global network of monitoring stations and radionuclide laboratories that constitute the international monitoring system of the Comprehensive Test Ban Treaty (CTBT) (Okal 2001; Richard 2002; Vivas Veloso *et al.* 2002; Wernsperger & Schlosser 2004). In addition, technological efforts have also led to the design of third- and fourth-generation reactors that are more resistant to proliferation attempts (Fahlen *et al.* 2007), as well as advances in pre-detonation nuclear forensics (Chivers, Lyles Goldblum, Isselhardt & Snider 2008).

Although technological solutions appear to offer a tantalizingly attractive way to ensure nonproliferation, we believe that this is a chimera. Technological solutions can only work when there is a credible enforcement mechanism that underlie them. For example, the mere detection of radioxenon isotopes that are characteristic of a nuclear test is insufficient to deter nonproliferation; some form of contingent punishment is required. Similarly, the successful attribution of characteristic signatures associated with nuclear forensics calls for an international fissile materials database. Such enforcement mechanisms are therefore unlikely to be technological, but rather political.

How, then, have these political solutions for nonproliferation performed? Unfortunately, not too well. The Fissile Material Cutoff Treaty (FMCT) has consistently failed to find political traction, while security promises based on the provision of a nuclear umbrella have rapidly eroded in the aftermath of the Cold War (Carpenter 1994). The lack of internal coherence among the 45 members of the Nuclear Suppliers Group has afforded India—a non-signatory of the NPT—to achieve a certain level of legitimacy as a nuclear weapons state (Squassoni 2008). Even bilateral political efforts aimed at limiting the spread of nonproliferation may suffer from , as states often find it in their strategic self-interest to deliver or receive sensitive nuclear assistance (Kroenig 2009a,b).

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If efforts at nonproliferation have demonstrated lukewarm success, efforts at disarmament have been even more anemic. The various editions of the Strategic Arms Reduction Treaty (START) have slowly chipped away at the bloated U.S. and Russian arsenals. The U.S. Department of Defense's FSU Threat Reduction programs—which finance the decommissioning of nuclear assets (both human and nonhuman)—have also helped ring-fence the indiscriminate transfer of sensitive nuclear material during this denuclearization process. Overall, however, disarmament efforts are sluggish at best, and have suffered from criticisms that the nuclear weapons states have not held up to their end of the NPT bargain. Even with some notable shifts in the stance of the U.S. nuclear policy community in recent years (Shultz, Perry, Kissinger & Nunn 2007, 2008), there is precious little optimism about the future of nuclear zero.

The modest track record of tackling nonproliferation issues on the basis of the first and second pillars suggests the need to look at how peaceful uses of nuclear energy can provide fresh insight on future policy ideas. The main policy upshot of our analysis in Section 2 points the way to what may, at first glance, seem like a tautological strategy: To reduce the incentives of a given country to acquire weapons, prevent the neighboring countries from going nuclear themselves. Paradoxically, nonproliferation begets nonproliferation.

However, as we have seen in this paper, the negative feedback loops that result from the presence of a nuclear neighbor are nontrivial, and so the strategy is not as circular as it sounds. Indeed, the individual economic self-interest of countries can lead to a stable, nonproliferation outcome, as long as new nuclear-armed states do not interfere with the original political-economic calculus.

4 Conclusion

Successfully addressing nuclear nonproliferation in the 21st century is likely to require a menu of complementary approaches. The record in terms of either technologically- or politically-based solutions has often been mixed. This paper contributes to the small, but growing, literature on how working with economic incentives can have a positive impact on security outcomes.[4] Such positive incentives build on the relatively neglected third pillar of the NPT to devise solutions that can advance NPT objectives.

The arguments that we raise, and the policy implications that we draw, fly directly in the face of deterrence theorists who argue for selective nuclear proliferation (Intriligator & Brito 1981; Mearsheimer 1990). The debate on the

[4]For example, Beardsley & Lim (2009) propose a system of nuclear codependency between two countries, by having one country (a less developed, more belligerent North) host nuclear reactors that are paid for by the other (a more developed, less belligerent South). They show that a stable, peaceful equilibrium can exist where the North never finds it in its interest to disrupt energy supplies, while the South is willing to pay the fixed costs of nuclear plant construction in exchange for a discounted stream of energy supply from the North.

merits and demerits of nuclear deterrence is an old one, and this paper will by no means settle this debate. Hopefully, however, the analysis presented here throws some useful grist into the mill.

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Appendix

Consider an environment with two countries, $\{1, 2\}$, both of which can choose to produce either nuclear power (Energy) or weapons (Guns), in addition to other economic goods (Food). For simplicity, we assume that the production of E and G are perfect substitutes, so that output of either of these in country i is given by

$$N_i = \epsilon E_i + \gamma G_i, \tag{A.1}$$

where $\epsilon, \gamma > 0$ are parameters capturing the degree of substitution between the two, and we assume for simplicity that these do not vary between countries. Although we have constrained the functional form of (A.1) to a quasilinear one, this technical assumption can actually be relaxed (although at the cost of computational complexity). In addition to the political and technological reasons laid out in the main text, a corner solution could still arise if we conceptualize the tradeoff in (A.1) as one between energy and *security*, and allow security to be tradable. In this case, standard theories of Ricardian comparative advantage would suggest that countries with a lower relative productivity advantage in the generation of security would choose to specialize in non-weapons production, and "import" their security from a nation for which security provision is comparatively advantageous (such as the United States).

To introduce some asymmetry between the two countries, we allow the intrinsic motivation of each country to differ; more specifically, we assume that Country 2 is pacifist and will only employ G in defense, while Country 1 has an incentive to initiate aggressive activity for the purposes of attaining some form of (ego) rent.

For (pacifist) Country 2, therefore, national production is subject to a Cobb-Douglas production technology between F and (A.1):

$$Y_2 = A_2 N_2^{\alpha} F_2^{\beta}, \tag{A.2}$$

where $\alpha, \beta > 0$ are parameters representing output elasticities, and A is a variable that captures appropriation given by

$$A_2 = \begin{cases} 1 & \text{if } G_1 = 0 \text{ or } G_2 > 0, \\ 1 - \phi & \text{otherwise,} \end{cases} \tag{A.3}$$

where $0 < \phi < 1$ is the share of output that is appropriated. Of course, in a nuclear confrontation it is unlikely that output is actually captured but rather simply destroyed; however, this interpretation does not affect the implications of the model.[5]

National production for (antagonist) Country 1 is subject to a similar Cobb-Douglas form

$$Y_1 = N_1^{\alpha} F_1^{\beta} + A_1 Y_2, \tag{A.4}$$

but in this case, appropriation from Country 1 appears as aggression rents where

$$A_1 = \begin{cases} \phi & \text{if } G_1 > 0 \text{ and } G_2 = 0, \\ 0 & \text{otherwise,} \end{cases} \tag{A.5}$$

where ϕ in this case is the multiplier on rent (measured in terms of foreign output) due to aggression.

Importantly, we have assumed that aggression rents, when nonzero, are exactly equal to the appropriation losses from the pacifist country. We recognize that this equality is more likely in the context of conventional war—where the victor receives the spoils directly from the share of forfeited production of the vanquished—but we maintain this for simplicity.[6]

Finally, we make an important assumption about the underlying production technologies that apply to a given set of inputs.

[5] In addition, it should be noted that any appropriation does not occur instantaneously, but rather reflects the likely losses in the event of escalation into actual conflict.

[6] One could easily remedy this by allowing an additional multiplicative parameter, say τ, to either moderate (if $\tau < 1$) or amplify (if $\tau > 1$) the effect of (A.5), but doing so simply adds an unnecessary complication to our model.

Assumption 1. Given (A.2) and (A.4): (a) $\{E_i, F_i\} \in Y_i \; \forall i = 1, 2 \Rightarrow \alpha, \beta \geq 1$; (b) $\{F_i, G_i\} \in Y_i \; \forall i = 1, 2 \Rightarrow \alpha = \delta < 1, \beta = (1 - \delta)$.

This assumption allows for returns to production to be increasing in the economically complementary activities of power and economic goods production (Assumption 1a), while returns to production of the economic substitutes of weapons and other goods are subject to standard constant returns (Assumption 1b). This assumption makes intuitive sense: Energy production is often an important input to the production of most economic goods, and hence conferring production externalities that lead to increasing returns, while weapons are generally used only for defense and any positive externality garnered from its presence accrues from its ability to prevent indiscriminate appropriation.

Note that the expressions given by (A.1)–(A.5) represent the underlying production structure of the agents in the game, not the actual payoffs that accompany a maximization program; doing so requires a full specification of the constrained optimization problem facing each country. To keep the model tractable, however, we abstract from the choice problem and assume that the variables given represent optimal values. We can then treat these expressions as (reduced-form) payoffs $V(\cdot)$ to the players in the game, so that $V(Y_i) = Y_i$.

Throughout the rest of the exposition, we utilize two standard equilibrium concepts, (simultaneous) Nash equilibrium and its temporal refinement, subgame perfect Nash equilibrium, and we only consider equilibria in pure strategies.

Definition 1 (Equilibria)**.** Let the strategy set for each country i be $s_i = \{e_i, g_i\}$ and feasible actions from this set be $q_i \in s_i$. Further, let the set of histories up till time t be given by h_t. Then:
(a) The (pure strategy) Nash equilibrium of the simultaneous game is given by the double $\{q_1^*, q_2^*\}$ induced by the profile $s = \{s_1^*, s_2^*\}$ such that $\forall \; i$: $\{\nexists \; \tilde{s}_i \neq s_i^*$ such that $Y_i(\tilde{s}_i) \geq Y_i(s_i^*)\}$.
(b) The (pure strategy) subgame perfect Nash equilibrium of the sequential game is given by the double $\{q_1^*, q_2^*\}$ induced by the profile $s = \{s_1^*, s_2^*\}$ such that $\forall \; i, t : \{\nexists \; \tilde{s}_i \neq s_i^*$ such that $Y_i(\tilde{s}_i | h_{t-1}) \geq Y_i(s_i^* | h_{t-1})\}$.

Again appealing to analytical tractability, we assume that for the sequential game, Country 1 always moves first. We can now state the first of the two central propositions of the paper.

Proposition 1 (Stable nonproliferation)**.** *Given Assumption 1, if $E_i = F_i = G_i \; \forall \; i$ and $\epsilon = \gamma$, then the following condition is sufficient to ensure nonproliferation in the simultaneous game:*

$$\phi < \frac{(\epsilon E_1)^{\alpha} F_1^{\beta} - (\epsilon E_1)^{\delta} F_1^{1-\delta}}{(\epsilon E_2)^{\alpha} F_2^{\beta}}. \quad \text{(A.6)}$$

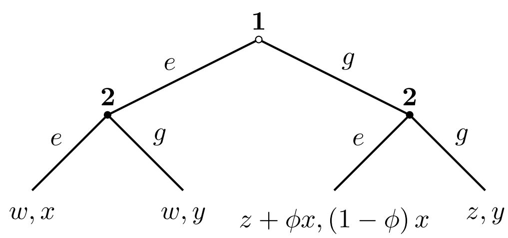
In the sequential game, the following condition is sufficient to ensure nonproliferation:

$$(1 - \phi) < (\epsilon E_2)^{\delta - \alpha} F_2^{1-\delta-\beta}. \quad \text{(A.7)}$$

Proof. To reduce notational clutter, we define the following: $w \equiv (\epsilon E_1)^{\alpha} F_1^{\beta}$, $x \equiv (\epsilon E_2)^{\alpha} F_2^{\beta}$, $y \equiv (\gamma G_2)^{\delta} F_2^{1-\delta}$, $z \equiv (\gamma G_1)^{\delta} F_1^{1-\delta}$. The payoffs in normal form are then (Country 1 payoffs listed first):

		Country 2	
		e	g
Country 1	e	w, x	w, y
	g	$z + \phi x, (1 - \phi) x$	z, y

Since $\alpha + \beta > 1$, $\delta < 1$, and $E_i = G_i$, the sufficient condition for an equilibrium with (e, e) is given by (A.6) (after some rearrangement). With Country 1 moving first, the payoffs in extended form are (Country 1 payoffs listed first):



In this case the sufficient condition for an equilibrium with (e, e) is given by (A.7) (after some rearrangement). □

The proposition essentially argues that the conditions required for stable nonproliferation are actually fairly easily attained. To see this, consider that the numerator of the right hand side of (A.6) will always be positive, so as long as the economic size of Country 2 (the denominator) is not too large relative to that of Country 1, the condition will be satisfied (since $\phi < 1$ by construction). In the sequential game the condition is potentially even less stringent, since the larger the appropriation/aggression rent, the smaller the left hand side of (A.7) will be, and so unless the economic size of Country 2 is extremely large the condition is likely to be satisfied.

To gain further traction, and without loss of insight, we populate our variables and parameters with numerical payoffs.

Assumption 2. (a) $\epsilon = \gamma = 1$; (b) $\alpha = 2$, $\beta = 1$, $\delta = 0.5$; (c) $E_i = F_i = G_i = 2 \; \forall \; i = 1, 2$.

These assumptions set: (a) the substitution factor between E and G to unity; (b) the output elasticity for E, F, and G to two, unity, and a half, respectively; (c) output elasticity for E to 2; (c) the optimal input values for E, F, and G to be equal, at 2. We allow the appropriation/aggression parameter to vary, since this generates the most interesting outcomes.

We are now in a position to explore the equilibria that result from several permutations to the payoffs.

Example 1 (Low appropriation in non-nuclear neighborhood)**.** Let $\phi = 0.5$. There is one simultaneous Nash equilibrium and one subgame perfect Nash equilibrium, and they both involve the strategy (e, e).

Example 2 (High appropriation in non-nuclear neighborhood)**.** Let $\phi = 0.875$. There are no simultaneous Nash equilibria and one subgame perfect Nash equilibrium, involving the strategy (e, e).

What is remarkable here is the stability of the peaceful equilibrium in this setup: Even in the high appropriation case demonstrated in Example 2, there will be a subgame perfect equilibrium in pure strategies involving the peaceful outcome. In fact, it is straightforward to show that, with the parameters given by Assumption ass:parameterization, the value of ϕ that leads to this indeterminacy in the simultaneous move game is $\phi = 0.75$. Thus, a fairly high degree of appropriation—or destruction, if viewed in that manner—is required to disrupt the stability of the simultaneous Nash equilibrium.

Consider now the introduction of a third country, Country 3, which we do not explicitly model, but for which we assume already has in its possession nuclear weapons. In this case, there are no longer any ego rents to be appropriated from possession of a nuclear arsenal. As a consequence, while national output of the (pacifist) Country 2 remains unchanged according to (A.2), that of the (antagonist) Country 1 now needs to be modified to become

$$Y_1' = A_1' N_2^{\alpha} F_2^{\beta}, \tag{A.8}$$

where the appropriation variable for both countries is now equal to

$$A_i' \begin{cases} 1 & \text{if } G_i > 0 \text{ or } G_{-i} = 0, \\ 1 - \phi & \text{otherwise,} \end{cases} \tag{A.9}$$

where G_{-i} is the set of all countries other than i.

As before, we appeal to analytical tractability and assume that for the sequential game, Country 1 moves first. We now arrive at our second central proposition.

Proposition 2 (Induced proliferation)**.** *Given Assumption 1, if $E_i = F_i = G_i\ \forall\ i$ and $\epsilon = \gamma$, then the following conditions are sufficient to lead to proliferation in both the simultaneous and sequential games:*

$$(1 - \phi) < (\epsilon E_i)^{\delta - \alpha} F_i^{1 - \delta - \beta} \qquad \forall\ i. \tag{A.10}$$

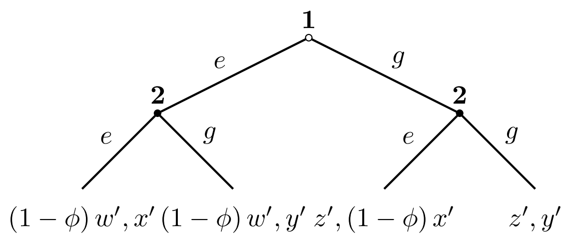
Proof. To reduce notational clutter, we define the following: $w' \equiv (\epsilon E_1)^{\alpha} F_1^{\beta}$, $x' \equiv (\epsilon E_2)^{\alpha} F_2^{\beta}$, $y' \equiv (\gamma G_2)^{\delta} F_2^{1-\delta}$, $z' \equiv (\gamma G_1)^{\delta} F_1^{1-\delta}$. The payoffs in normal form are then (Country 1 payoffs listed first):

Since $\alpha + \beta > 1$, $\delta < 1$, and $E_i = G_i$, the sufficient conditions for an equilibrium with (g, g) are given by the two equations

$$(1 - \phi) < (\epsilon E_1)^{\delta - \alpha} F_1^{1 - \delta - \beta},$$
$$(1 - \phi) < (\epsilon E_2)^{\delta - \alpha} F_2^{1 - \delta - \beta},$$

		Country 2	
		e	g
Country 1	e	$(1-\phi)\, w', x'$	$(1-\phi)\, w', y'$
	g	$z', (1-\phi)\, x'$	z', y'

which can be re-expressed as (A.10). With Country 1 moving first, the payoffs in extended form are (Country 1 payoffs listed first):



The sufficient conditions for an equilibrium with (g, g) are as before, and given by (A.10). □

Notice that each of the two conditions in Proposition 2 is analogous to (A.7) in Proposition 1, except that now the satisfaction of the condition *will lead to proliferation.* The ease of which these conditions can be met have already been discussed; what remains to be pointed out is that we require the concurrent satisfaction of the condition in *both* countries. While this may or may not be likely, by again imposing the numerical values listed in Assumption 2, we can gain useful intuition on the nature of the result.

Example 3 (Low appropriation in nuclear neighborhood)**.** Let $\phi = 0.5$. There is one simultaneous Nash equilibrium and one subgame perfect Nash equilibrium, and they both involve the strategy (e, e).

Example 4 (High appropriation in nuclear neighborhood)**.** Let $\phi = 0.875$. There is one simultaneous Nash equilibrium and one subgame perfect Nash equilibrium, and they both result in the strategy (g, g).

Using the same parameterization as before now tells a very different story. While it is the case that moderate levels of appropriation would not lead to a drive toward the acquisition of nuclear weapons (Example 3), as long as losses resulting from a nuclear attack exceed a certain threshold ($\phi > 0.75$ given these parameters), there will be a strong incentive to establish a nuclear arsenal by both the pacifist as well as antagonist nation. Essentially, the introduction of a nuclear presence into a regional neighborhood leads to the entire neighborhood ultimately choosing to build nuclear weapons instead of engaging in peaceful uses of nuclear power.