information systems data on the nature of interstate borders and PRIO's datasets on petroleum and diamond resources, shared river basins, and length of international boundaries.

For additional perspectives on offense-defense theory, see the edited volumes of Brown, Coté, Lynn-Jones, and Miller (2004) and Gortzak, Haftel, and Sweeney (2005). The effects of weapons technologies on intergroup violence are also assessed in the military history literature (see, e.g., Rotte and Schmidt 2003) and in the nonprovocative defense literature (see, e.g., Fischer 1984, Wiseman 2002).

During much of the twentieth century, the Lanchester model constituted the foundation of mathematical war modeling (Taylor 1983). Although Lanchester theory has been criticized by war modelers (e.g., Epstein 1985, Ancker 1995), it is still used in military service organizations to assess various dynamic aspects of war (Epstein 1985, p. 3) and in academic articles on war risk and duration (Bellany 1999, Anderton and Carter 2007). Lanchester-type models have also been used to study, among other things, terrorist recruitment (Faria and Arce 2005), guerrilla warfare (Intriligator and Brito 1988), peacekeeping (Gaver and Jacobs 1997), primitive warfare among people groups (Beckerman 1991), historical battles (e.g., Weiss 1966, Hartley and Helmbold 1995, Lucas and Turkes 2003), and war among social animals and insects (e.g., Adams and Mesterton-Gibbons 2003, Plowes and Adams 2005). For an extensive overview of quantitative methods of combat analysis, see Przemieniecki (2000).

Political economy models of the consolidation or fragmentation of states emphasize a variety of variables to explain the size and number of nations in the international system, including taxation (Buchanan and Faith 1987), wealth maximization (Wittman 2000), trade openness (Alesina, Spolaore, and Wacziarg 2000), citizens' policy preferences (Bolton and Roland 1997), states' ability to defend property (McGuire 2002), international conflict and the cost of defense (Alesina and Spolaore 2006), and civil conflict (Spolaore 2008a). Spolaore (2008b) offers a concise review of the literature. For a forum on fragmented states and trans-state groups, see Stanislawski (2008). The Federation of American Scientists provides an extensive list of para-state entities, many of which can be characterized as trans-state groups (www.fas.org/irp/world/para/index.html).

10

Arms Rivalry, Proliferation, and Arms Control*

Born in the tense early years of the Cold War, conflict economics has long been interested in arms rivalry, proliferation, and arms control. In this chapter we provide a summary of key principles and research results in this historically important branch of conflict economics. We begin with definitions followed by an empirical overview of military spending, weapons of mass destruction, and arms control treaties. We then return to the historical roots of conflict economics by sketching the seminal arms race models of Richardson and Intriligator and Brito. To these we add a rational choice model that highlights the interdependence of economics and security in issues of defense spending, arms rivalry, and arms control. Applications to historical and contemporary arms rivalries are presented, including possible proliferation of nuclear weapons to Iran, strategic implications of deployment of US antiballistic missile technology in Europe, and decay of the Soviet economy during the Cold War. We also briefly survey selected empirical studies, focusing on the structure of interstate arms rivalries, arms racing and the risk of war, and risk factors for nuclear weapons proliferation.

10.1. Definitions

An arms rivalry is a competitive increase in the weapons quantities or qualities of two or more parties. Arms rivalries are typically thought of as occurring between states, but they can also occur within states and can

* Sections 10.1, 10.3, and parts of 10.4 and 10.6 of this chapter are adapted from Charles H. Anderton and John R. Carter, "A Survey of Peace Economics," published in *Handbook of Defense Economics*, volume 2, edited by Todd Sandler and Keith Hartley, pp. 1211–1258, Copyright © Elsevier 2007. We gratefully acknowledge Elsevier's permission to republish material from the article.

involve transnational groups. Although the terms "arms rivalry" and "arms race" are often used interchangeably, an arms race is a special case of arms rivalry and is characterized by an unusually rapid rate of increase in weapons quantities or qualities. Proliferation is an increase in the number of parties obtaining weapons of mass destruction; it can grow out of an arms rivalry and can spawn new rivalries.

There are three major classes of weapons that states and non-state groups might acquire: major conventional weapons, such as tanks, destroyers, and fighter aircraft; small arms and light weapons, such as machine guns, assault rifles, and improvised explosive devices; and weapons of mass destruction, including nuclear, biological, chemical, and radiological weapons. Major conventional weapons are predominant in interstate wars, while small arms and light weapons are used extensively by non-state groups in intrastate and extra-state conflicts. Weapons of mass destruction can cause enormous casualties and destruction and can be developed directly or acquired through trade by states or by non-state groups (Anderton and Carter 2008a).

Based on Schelling and Halperin's (1961) classic text, arms control refers to all forms of military cooperation between potential adversaries designed to reduce (1) the risk of war, (2) the damage should war come, and (3) the economic and political costs of military preparation. This conception of arms control asserts a common interest between enemies, with the possibility of reciprocation and cooperation over military postures. The forms of cooperation might include changes in political or military communications, modes of force deployment, quantity or quality of weapons, and rates of weapons accumulation. Note that Schelling and Halperin's three goals of arms control are distinct, which raises the possibility of trade-offs among them.

10.2. Patterns of Arms Rivalry, Proliferation, and Arms Control

Arms Rivalry

Figure 10.1 summarizes the trend in worldwide real (inflation-adjusted) military spending from 1988 through 2007. The high spending level during the latter years of the Cold War is not surprising given the pervasive geopolitical significance of the US-Soviet rivalry at the time. The reductions in the late 1980s and early 1990s reflected a hoped-for peace dividend following the decline of the Cold War, while the increases in the 2000s

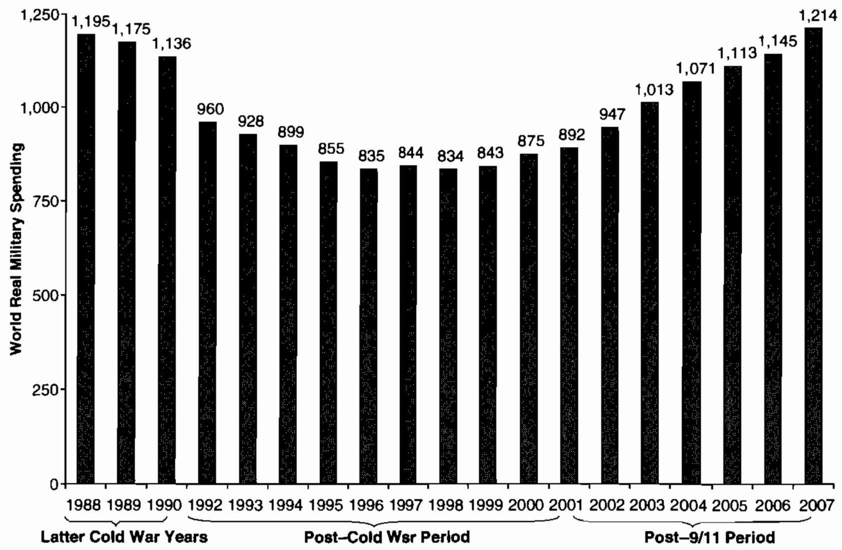

Figure 10.1. World real military spending, 1988–2007 (in billions of US dollars at constant 2005 prices and exchange rates).
Note: Military spending for 1991 is not reported owing to incomplete data for Eastern Europe.
Source: Data used with permission courtesy of Stockholm International Peace Research Institute (www.sipri.org).

correspond in part to the new challenges of terrorism faced by many nations. Notice in recent years that annual spending has been greater than one trillion dollars. To appreciate the economic enormity of such resource diversion, consider that world military spending of \$1.1 trillion in 2005 easily exceeded Africa's total gross domestic product of \$817 billion (International Monetary Fund 2007).

Figure 10.2 shows real military-spending patterns for selected years for four well-known interstate arms rivalries. We designate these cases as arms rivalries for three reasons. First, each shows a general increase in real military spending, a frequent proxy for armaments, over the periods specified. Second, according to Thompson (2001, p. 560), the actors in each dyad were involved in a strategic rivalry, whereby each regarded the other as a competitor, an enemy, and a source of threats that could become militarized. Third, Gibler, Rider, and Hutchison's (2005) review of historical accounts indicated that each rival pair in Figure 10.2 increased armaments or military personnel competitively for some of the years shown.

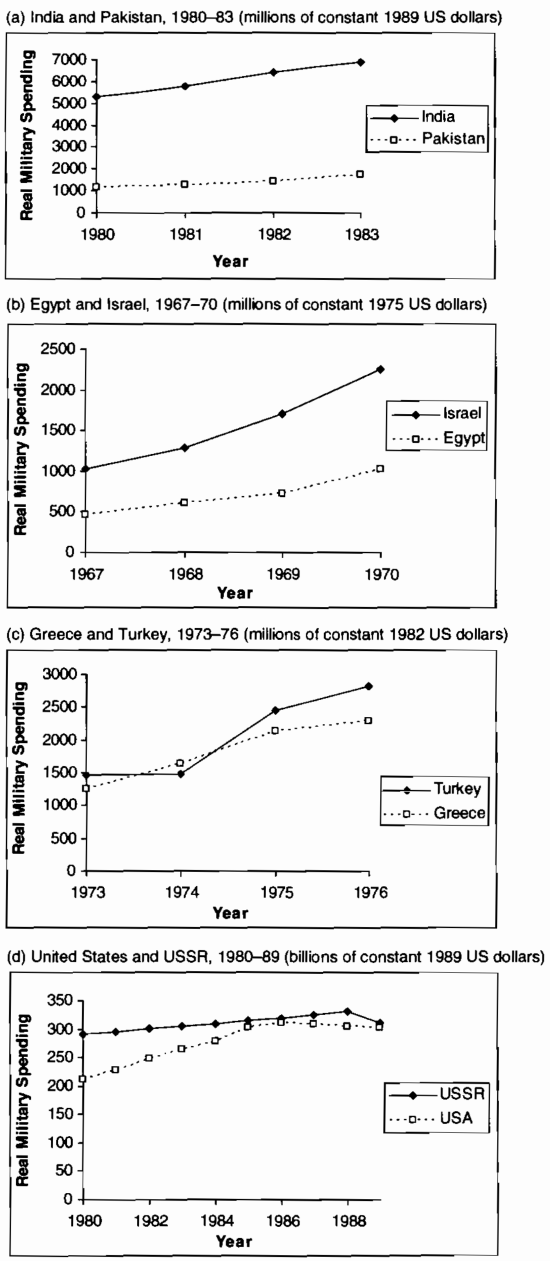

Figure 10.2. Real military-spending patterns in selected interstate arms rivalries.
Source: ACDA (1978, 1985, 1990).

But are the four cases in Figure 10.2 arms races? In our view, panels (a)–(c) suggest arms racing for the years shown, but panel (d) does not. In the first three panels, the average annual growth rates in real military spending were 9.1 percent for India and 15.6 percent for Pakistan, 30.2 percent for Israel and the same for Egypt, and 24.2 percent for Turkey and 22.0 percent for Greece. These growth rates represent unusually rapid increases in real military spending for the periods shown. Moreover, measuring military spending as a percentage of gross national product, each nation's defense burden rose between the first and last year: from 3.2 to 3.5 percent for India, 5.4 to 6.8 percent for Pakistan, 16.1 to 25.0 percent for Israel, 6.7 to 12.8 percent for Egypt, 3.9 to 6.0 percent for Turkey, and 4.0 to 6.7 percent for Greece (ACDA for various years).

The US-Soviet case in panel (d) does not depict arms racing in our view, even over the more limited period 1980–85. From 1980 to 1985, real military spending by the United States rose at an average annual rate of 7.4 percent, which we would count as unusually rapid. For the Soviet Union, however, real military spending grew at an average annual rate of only 1.6 percent over the same period.

Proliferation

Since the beginning of the Cold War, the spread of weapons of mass destruction (WMD) to states and non-state groups has received much attention by scholars and policy makers. At the time of this writing, there exist concerns about nuclear weapons programs in Iran and North Korea. There is also growing anxiety about the potential of terrorist organizations to acquire nuclear weapons (Allison 2004, Howard and Forest 2008). Even if a terrorist organization were unable to create a nuclear detonation, it could spread deadly radioactivity by causing an explosion at a nuclear power reactor or by using a radiological dispersion device known as a dirty bomb.

Nuclear weapons create enormous explosive yield through the fission of heavy atoms such as uranium or plutonium (for an atomic bomb) or the fusion of light atoms like hydrogen (for a hydrogen bomb). The atomic bomb dropped on Hiroshima in 1945 had an explosive force of 12 kilotons of TNT equivalent and resulted in approximately 140,000 deaths. Sixteen years later the Soviet Union tested a hydrogen bomb with an explosive yield of 50 megatons, about four thousand times more powerful than the bomb at Hiroshima (Perkins 1991, p. 23).

Biological weapons use microorganisms such as bacteria and viruses to kill or incapacitate humans, livestock, or crops. Diseases that might be unleashed by biological weapons include anthrax, cholera, plague, smallpox, botulism, and Ebola. The lethality of a biological attack can vary widely depending on dispersal methods, health responses, weather conditions, and contagiousness of the biological agent. In the fall of 2001, a number of anthrax-laced letters were mailed to various parties in the United States by an unknown perpetrator, leading to five deaths. In Japan in the early 1990s, the Aum Shinrikyo cult attempted a number of large-scale biological attacks in Tokyo using anthrax. The attacks failed because the cult mistakenly weaponized a nonvirulent form of anthrax. If not for Aum Shinrikyo's technical error, the number of casualties could have been substantial.

Chemical weapons use nonliving toxic chemicals to kill or incapacitate humans, livestock, or crops. Chemical weapons can be based on nerve agents such as tabun, sarin, or VX; blister agents such as sulphur mustard, nitrogen mustard, or lewisite; protein synthesis inhibitors such as ricin; or choking agents such as phosgene or chlorine. Iraq used tabun against Iranian forces during the 1980–88 war. Iraq also used nerve and blister agents to attack the Kurdish city of Halabja in 1988, with fatality estimates ranging from a few hundred to 7,000. In 1995, the Aum Shinrikyo cult unleashed sarin in the Tokyo subway, leading to 12 fatalities and more than 1,000 injuries.

Table 10.1 summarizes the estimated effects of large-scale WMD attacks on area and people based on hypothetical simulations reported in various studies. The first four rows compare the effects of nuclear, biological, and chemical weapons attacks. These studies reveal that biological weapons have the same or even greater potential to affect area and cause casualties than do nuclear weapons, while chemical weapons are less devastating. Of particular concern are the results of the studies on biological-line attacks summarized in the final two rows. In a line attack, a crop duster or ground vehicle with a specialized spray tank spreads a biological agent along a line so that prevailing winds disperse the agent over a population center. As Table 10.1 shows, a biological line attack has the potential to affect a vast area and cause hundreds of thousands of casualties.

In Figure 10.3 we show by decade the number of nations with nuclear weapons research programs and the number with actual nuclear weapons. In the 1940s, only the United States and the Soviet Union possessed nuclear weapons. By the 1960s, the nuclear group had grown to include the United Kingdom, France, and China. By the 1980s, India, Israel, and probably South Africa had joined the nuclear club. By the 2000s, South Africa had dismantled its nuclear program, but Pakistan and possibly North Korea had added weapons. The figure shows that more states have been suspected of nuclear weapons research than have developed actual weapons. Hence, it is

Table 10.1. *Estimated effects of large-scale weapons of mass destruction attacks.*

Selected Study	Weapon System	Area Affected (km^2)	Casualties
United Nations (1969)	1 mt nuclear 10 t biological 15 t nerve agent	300 100k 60	90% killed 50% ill; 25% killed 50% killed
Robinson, Hedén, and Schreeb (1973) – bomber attack	10 kt nuclear biological agent VX nerve gas 5 t–6 t high explosive	30 0–50 0.75 0.22	
Fetter (1991) – missile attack on sparsely populated city	20 kt nuclear 30 kg anthrax spores 300 kg sarin		40k killed; 40k injured 20k–80k killed 200–3,000 killed
Office of Technology Assessment (1993) – missile attack on city with sparse-to-moderate population	12.5 kt nuclear 30 kg anthrax spores 300 kg sarin	7.8 10 0.22	23k–80k killed 30k–100k killed 60–200 killed
United Nations (1969) – line attack	biological agent at concentration of 10^{10} per gm along 100 km line	5k	50% killed
Office of Technology Assessment (1993) – line attack	100 kg anthrax spores	46 (clear day) 140 (overcast) 300 (clear night)	130k–460k killed 420k–1.4m killed 1m–3m killed

Sources: Studies shown in first column and Dando (1994, p. 5).

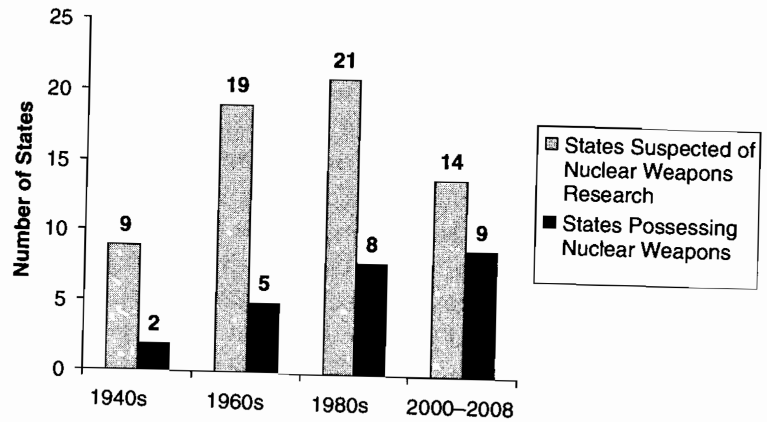

Figure 10.3. Number of states suspected of nuclear weapons research and possession. *Sources*: Singh and Way (2004) and James Martin Center for Nonproliferation Studies (http://cns.miis.edu/).

possible that far more states could have come to possess nuclear weapons than actually do. Still, the number of states possessing nuclear weapons has continued to rise over the decades from two in the 1940s to probably nine in recent years. For a range of views on the danger posed by nuclear proliferation, see Sagan and Waltz (2002) and Goldstein (2006).

Table 10.2 summarizes the status of WMD proliferation for selected states as of 2007. The first column of data shows that eight, and probably nine, states possess nuclear weapons, while Iran is believed by many analysts to be carrying out research consistent with nuclear weapons development. The next column shows the number of nuclear warheads in each nuclear state's arsenal. A wide range of nuclear warheads is reported for the United States and Russia, with the upper estimates encompassing thousands of warheads in reserve or awaiting dismantlement. The columns on biological and chemical weapons show the recent status of various nations' programs in these areas. The final column offers a brief summary of WMD delivery capabilities, including the range available to each nation. We qualify the data in Table 10.2 by acknowledging that there exists disagreement about the classification of states' WMD stocks and programs, particularly for biological and chemical weapons and for the number of North Korean nuclear warheads. The table reflects our conservative interpretation of information available in the sources indicated.

Arms Control

During and after the Cold War, the United States and Russia negotiated numerous arms control agreements to limit or reduce nuclear warheads, missiles, ballistic missile defenses, conventional forces, and other weapons technologies. Table 10.3 summarizes selected US-Russia arms control agreements. Note that some agreements, such as SALT I and SALT II, limited nuclear delivery systems (e.g., intercontinental ballistic missiles [ICBMs] and submarine-launched ballistic missiles [SLBMs]), but they put no brake on the number of nuclear warheads. Other treaties, such as START II and SORT, were designed to reduce the number of strategic warheads. The ABM Treaty limited each side's ability to defend itself in a nuclear attack, and START II reduced multiple independently targetable reentry vehicles (MIRVs), which allow one missile to carry multiple warheads.

The agreements shown in Table 10.3 represent traditional arms control, whereby detailed formal agreements are used by rivals to achieve one or more of Schelling and Halperin's arms control objectives. During the Cold War, arms control advocates viewed formal agreements to limit weapons

Table 10.2. *Proliferation of weapons of mass destruction for selected nations, 2007.*

Nation	Nuclear	Estimated Number of Warheads	Biological	Chemical	Delivery System Capability[a]
US	Known weapons	5,045–10,000[b]		Eliminating weapons	ICBM, SLBM, aircraft; range = 16,000 km
Russia	Known weapons	5,614–15,000[b]	Suspected research	Eliminating weapons	ICBM, SLBM, aircraft; range = 15,000 km
UK	Known weapons	160–195			SLBM; range > 7,400 km
France	Known weapons	348			SLBM, aircraft; range = 6,000 km
China	Known weapons	145–200			ICBM, SLBM, aircraft; range=13,000 km
Israel	Known weapons	≤100	Suspected research	Suspected research	MRBM, IRBM, aircraft; range = 4,000 km[c]
India	Known weapons	50		Eliminating weapons	SRBM, MRBM, aircraft; range > 2,000 km
Pakistan	Known weapons	60			SRBM, MRBM, aircraft; range = 1,600 km
North Korea	Suspected weapons	0–6	Suspected weapons	Known weapons	SRBM, MRBM, ICBM; range = 1,300 km[d]
Iran	Suspected research				
Egypt				Suspected weapons	
Syria			Suspected research	Known weapons	
Libya				Eliminating weapons	

Notes: SRBM – Short-range ballistic missile (<1,000 km), MRBM – Medium-range ballistic missile (1,000–3,000 km), IRBM – Intermediate-range ballistic missile (3,000–5,500 km), ICBM – Intercontinental ballistic missile (>5,500 km), SLBM – Submarine-launched ballistic missile.

[a] The delivery system ranges reported are high-end estimates, which are not necessarily the maximum ranges attainable based on range-extension technologies such as lighter payloads or postboost vehicle enhancements (see National Air and Space Intelligence Center 2006).

[b] The first number is an estimate of operational nuclear warheads; the second number is an estimate of operational warheads plus warheads held in reserve or awaiting dismantlement.

[c] Stockholm International Peace Research Institute (2007, p. 548) reports that if Israel converted its Shavit space launch vehicle to a ballistic missile, a 775 kg payload could be delivered a distance of 4,000 km.

[d] The range estimate reported for North Korea is for the Nodong MRBM. As of 2007, many analysts do not believe that North Korea's Taepodong-2 ICBM is functional.

Sources: Stockholm International Peace Research Institute (2007) for nuclear warheads and delivery capability for the first nine countries listed. The remaining information is our interpretation of WMD country profiles provided by the James Martin Center for Nonproliferation Studies (http://cns.miis.edu/).

Table 10.3. *Selected US-Russia (USSR) arms control treaties.*

Arms Control Treaty	Summary Description
Strategic Arms Limitation Talks I (SALT I); entered into force: 1972	Limited the number of intercontinental and submarine-launched ballistic missiles and ballistic missile submarines. Included Anti-Ballistic Missile Treaty to limit strategic defensive systems.
Treaty on the Limitation of Anti-Ballistic Missile Systems (ABM Treaty); entered into force: 1972 US withdraws from treaty: 2002	Each side limited antiballistic missile (ABM) systems to two sites (national capital and around ICBM silos) separated by at least 1,300 km, with no more than 100 ABM interceptor missiles at each site.
Strategic Arms Limitation Talks II (SALT II); signed: 1979 (never entered into force) US announces nonabidance: 1986	Included the following limits on each side: 2,400 strategic nuclear delivery vehicles (ICBMs, SLBMs, and heavy bombers), 1,320 multiple independently targetable reentry vehicles (MIRVs), and no new construction of land-based ICBMs.
Intermediate-Range Nuclear Forces Treaty (INF Treaty); entered into force: 1988	Committed the parties to eliminate medium-to-intermediate-range (1,000–5,500 km) and short-range (500–1,000 km) missiles.
Conventional Forces in Europe Treaty (CFE Treaty); entered into force: 1992 Russia suspends participation: 2007	Established equal limitations on major conventional forces for NATO and Warsaw Pact states, including 20,000 battle tanks, 30,000 armored combat vehicles, 20,000 artillery pieces, 6,800 combat aircrafts, and 2,000 attack helicopters.
Strategic Arms Reduction Treaty II (START II); signed: 1993 Extension protocol signed: 1997 Russia withdraws from treaty: 2002	By the end of 2004, the parties were to reduce their total deployed strategic nuclear warheads to 3,800–4,250. By the end of 2007, each party's total number of deployed strategic nuclear warheads was to be no more than 3,000–3,500, and all MIRVs were to be eliminated from ICBMs.
Strategic Offensive Reductions Treaty (SORT) (Moscow Treaty); entered into force: 2003	By the end of 2012, each party is to limit the aggregate number of strategic nuclear warheads to 1,700–2,200.

Source: James Martin Center for Nonproliferation Studies (http://cns.miis.edu/).

as an essential element of foreign policy that reduced the risk of war and the costs of military preparation. Arms control opponents maintained that formal agreements were vulnerable to cheating, did little to dampen US-Soviet development of nuclear and conventional weapons capabilities, and did not stem superpower-related conflict in other parts of the world. Disagreements between arms control proponents and opponents sometimes led to political stalemates over arms control treaties. For example, in the United States the SALT II Treaty was signed by President Carter but was never ratified by the US Senate. President Carter declared that the United States would comply with the treaty as long as the USSR reciprocated. Soviet general secretary Brezhnev made a similar statement regarding Soviet compliance. In 1986, President Reagan announced that the United States would no longer abide by SALT II.

Traditional arms control was important during the Cold War, and it will probably retain some salience for the United States, Russia, and other states in the years ahead. For example, Levi and O'Hanlon (2005, pp. 124–126) maintain that the Conventional Forces in Europe Treaty could provide a model for controlling conventional weapons on the Korean Peninsula. In addition to traditional arms control approaches, many states involved in arms rivalries will utilize less formal approaches to arms control, such as unilateral reductions in weapons and confidence-building measures. All of that said, it is likely that efforts to stem the proliferation of weapons of mass destruction to new states and non-state groups will dominate the arms control agenda in the immediate decades ahead.

Table 10.4 summarizes selected nonproliferation treaties and programs designed to limit the spread of nuclear, biological, and chemical (NBC) weapons technologies and missile delivery systems around the world. The first three treaties in the table concern nonproliferation of nuclear weapons, while the next two target biological and chemical weapons proliferation. The Missile Technology Control Regime focuses on the proliferation of particularly fast means of delivery of WMD. The final two programs in the table aim at controlling WMD materials of former Soviet states and the illicit shipment of WMD materials by states or non-state organizations. These programs are noteworthy because of persistent reports about the loss or theft of weapons-grade nuclear materials from the former Soviet Union and the fear that these materials could end up in the hands of terrorists.

A fundamental difficulty associated with efforts to control the spread of NBC weapons is their dual-use nature. Nuclear facilities for enriching uranium and reprocessing plutonium for nuclear energy purposes can be converted to produce nuclear weapons-grade material. Virtually all of the

Table 10.4. *Selected nonproliferation treaties and programs.*

Nonproliferation Treaty or Program	Summary Description
Non-Proliferation Treaty (NPT); entered into force: 1970 Current membership: 188 states	The "five nuclear weapons states" (US, Russia, UK, France, and China) agree to not transfer nuclear weapons technologies to any other parties and to pursue negotiations in good faith toward general and complete disarmament. Nonnuclear weapons states agree to not receive nuclear weapons technologies from any transferor and to not manufacture nuclear weapons.
Comprehensive Test Ban Treaty (CTBT); opened for signature: 1996 Number of signatories: 176 states	Any nuclear weapon explosion for testing or peaceful purposes is prohibited.
Treaty of Tlatelolco; entered into force: 1969 Current signatories: 33 Latin American and Caribbean states	Prohibits testing, use, production, storage, or acquisition of nuclear weapons by the parties or on behalf of anyone else.
Biological and Toxin Weapons Convention (BTWC); entered into force: 1975 Number of signatories: 169 states	Parties agree to not develop, produce, stockpile, or acquire biological agents or toxins for hostile purposes or for armed conflict and to not assist a recipient in acquiring any of the agents, toxins, weapons, equipment, or means of delivery.
Chemical Weapons Convention (CWC); entered into force: 1997 Number of signatories: 186 states	Parties agree to not develop, produce, stockpile, or acquire chemical weapons, to not assist others in acquiring or using chemical weapons, and to not engage in military preparations for use of chemical weapons. Each party agrees to destroy all chemical weapons and chemical weapons production facilities it possesses.
Missile Technology Control Regime (MTCR); established: 1987 Number of members: 34 states	An informal association of states that follows guidelines to stem the proliferation of missiles, unmanned air vehicles, and related technologies.
Cooperative Threat Reduction Program (CTRP) (Nunn-Lugar Program); established: 1991	Provides funding and expertise to the new independent states of the former Soviet Union (e.g., Russia, Belarus, Ukraine, Kazakhstan) to dismantle WMD and to enhance the security of nuclear weapons and fissile materials associated with dismantlement.
Proliferation Security Initiative (PSI); established: 2003 Number of members: 15 states	Encourages states to develop a broad range of legal, diplomatic, economic, and military means to interdict threatening shipments of WMD and missile-related technologies via air, land, and sea.

Source: James Martin Center for Nonproliferation Studies (http://cns.miis.edu/).

technologies and many of the precursor materials necessary to produce biological and chemical weapons are used in the production of civilian goods. Hence, it is relatively easy for states to take first steps toward nuclear weapons under the guise of peaceful nuclear energy development and to hide production of biological and chemical weapons within civilian infrastructure. This suggests that robust inspection regimes are necessary to control WMD developments. Nevertheless, the ability of states or non-state groups to hide biological weapons development in small labs implies that traditional approaches to international inspection are unlikely to be effective in controlling such weapons (Levi and O'Hanlon 2005, p. 75).

Despite the emphasis of past and present arms control initiatives on WMD and major conventional weapons, most casualties in armed conflicts around the world are due to small arms and light weapons (SALW) such as assault rifles, machine guns, rocket-propelled grenades, and improvised explosive devices. Stemming the production and trade of SALW can be difficult because of the large number of producers and recyclers of such weapons, the potential for such activities to generate commercial profits, and the ability of suppliers to bypass government controls. Nevertheless, some preliminary efforts to monitor and control the flow of SALW are underway. Table 10.5 summarizes selected conventions and protocols designed to stem the trade in SALW. The table implies that SALW control is being promoted by a mixture of governmental and nongovernmental organizations, whereas traditional arms control and nonproliferation regimes tend to be initiated by states. Although most current approaches to SALW control are limited in scope to a single type of weapon (e.g., anti-personnel mines) or region (e.g., the Nairobi Protocol) and thus are vulnerable to the substitution principle, they have encouraged governments to alter their SALW production and trade policies.

10.3. The Richardson Arms Race Model

A common theoretical starting point for the study of arms rivalry is the one-play and repeated prisoners' dilemma games described already in Chapter 4. Here we move on to the well-known Richardson model, which has been used in a vast number of theoretical and empirical studies of arms rivalry.

In the context of growing tension between the United States and the Soviet Union in the 1950s, Richardson's (1939, 1960a) mathematical model of arms rivalry captured the imagination of a growing number of social scientists, particularly from political science. What was significant to this community of scholars was Richardson's conviction that arms rivalry,

Table 10.5. *Selected SALW control organizations and protocols.*

Organization or Protocol	Summary Description
United Nations Conference on the Illicit Trade in Small Arms and Light Weapons; established: 2001	Conference involved representatives from states, international organizations, and NGOs. States agreed to a Programme of Action whereby various steps would be undertaken to improve control of SALW trade.
Nairobi Protocol; entered into force: 2006 Signatories: 12 states	Commits states to concrete actions (e.g., mandatory gun registration and ban on civilian ownership of military assault rifles) to control small arms in the Horn of Africa and the African Great Lakes region.
Middle East North Africa Action Network on Small Arms; established: 2002	An association of NGOs from Iraq, Jordan, Lebanon, Palestine, North Sudan, Syria, and Yemen facilitating actions by communities, NGOs, and governments to lessen the demand for SALW.
Antipersonnel Mine-Ban Treaty (also known as the Ottawa Convention); entered into force: 1999 Signatories/ Accession: 156 states	Binds each party to not use, develop, produce, acquire, stockpile, or transfer antipersonnel mines; to destroy all antipersonnel mines it possesses within four years; and to clear all laid landmines under its jurisdiction within 10 years.
International Action Network on Small Arms (IANSA); established: 1998 Affiliates: 700+ NGOs	A global network of civil society organizations working through national and local legislation, regional agreements, public education, and research to stop the proliferation and misuse of small arms and light weapons.

Sources: James Martin Center for Nonproliferation Studies (http://cns.miis.edu/), International Campaign to Ban Landmines (www.icbl.org), International Action Network on Small Arms (www.iansa.org), Middle East North Africa Network on Small Arms (www.mena-small-arms.org).

the risk of war, and other international relations phenomena could be fruitfully studied with mathematics and statistics. Some consider Richardson's arms race model and statistical methods to be crude by today's standards, but his (and Quincy Wright's) vision of applying scientific methods to the study of war and peace became the wellspring for numerous organizations and journals devoted to quantitative research on conflict, including the Peace Science Society (International), Correlates of War Project, *Journal of Conflict Resolution*, *Journal of Peace Research*, and *Conflict Management and Peace Science*.

Richardson's Differential Equations

Let M_A and M_B be the military stocks of two rival players A and B, while $\dot{M}_A$ and $\dot{M}_B$ are the rates of change in military stock per unit of time. Richardson hypothesized that three factors would affect a player's military buildup: (1) the insecurity created by the rival's military stock, (2) the fatigue or expense of the player's own military stock, and (3) the grievances or ambitions of the player toward the rival. The three factors are embodied in the Richardson arms race model, which is characterized by the following differential equations:

$$\dot{M}_A = kM_B - aM_A + g \qquad (10.1)$$

$$\dot{M}_B = rM_A - \beta M_B + h. \qquad (10.2)$$

In equations (10.1) and (10.2), k and r are reaction parameters that reflect how sensitive or insecure each player is to the military stock of its rival, while a and β are fatigue parameters representing the economic or political costs of a player's own military stock. Parameters g and h are grievance or ambition terms, representing sources of hostility between the players, such as past conflicts or territorial disputes.

Reaction Functions and Equilibrium

In the Richardson model, A adjusts its military stock until the elements on the right side of the equality in equation (10.1) are such that $\dot{M}_A = 0$. Intuitively, $\dot{M}_A = 0$ means that A's desired change in military stock is zero. By the same reasoning, $\dot{M}_B = 0$ signifies that B does not want to change its own military stock. By setting $\dot{M}_A$ and $\dot{M}_B$ equal to zero in equations (10.1) and (10.2), the following reaction functions for A and B can be derived:

$$M_A = \left(\frac{k}{a}\right)M_B + \left(\frac{g}{a}\right) \qquad (10.3)$$

$$M_B = \left(\frac{r}{\beta}\right)M_A + \left(\frac{h}{\beta}\right). \qquad (10.4)$$

A reaction function shows the level of military stock that each player chooses in response to the level of military stock of its rival. Equilibrium military stocks (M_A^*, M_B^*) are then found by solving the two equations (10.3) and (10.4) simultaneously for M_A and M_B, yielding:

$$M_A^* = (kh + \beta g)/(a\beta - kr) \quad (10.5)$$

$$M_B^* = (rg + ah)/(a\beta - kr). \quad (10.6)$$

Arms Race Stability

Although Richardson did not formally study the relationship between arms rivalry and the risk of war, it is clear from his writings that he was particularly concerned about the risk of war associated with an unstable arms rivalry. Given an initial increase in military stocks above the equilibrium, a rivalry is said to be unstable if the players react by further building up their stocks, and it is said to be stable if they respond by reducing their stocks back toward the equilibrium levels. In the Richardson model, the arms rivalry equilibrium can be shown to be stable when $(k/a)(r/\beta) < 1$. Note that the stability condition is governed by the slope terms, k/a and r/β, of the reaction functions in equations (10.3) and (10.4). If each player is sufficiently insecure and hence sensitive to its rival's armaments, so that k and r are large, relative to the cost of building weapons, shown by a and β, then $(k/a)(r/\beta)$ will be greater than one, giving rise to an unstable arms rivalry. Under these conditions, an arms rivalry could become a true arms race, with accelerating armaments leading to growing fears and suspicions and an elevated risk of war (Richardson 1960a, p. 61). Hence, in Richardson's view, limiting weapons buildups in an unstable arms rivalry could contribute to all three of Schelling and Halperin's arms control objectives: reduced risk of war, less damage should war come, and lower costs of military preparations.

Numerical Examples

Assume the following symmetric values for the reaction, fatigue, and grievance parameters of the Richardson model: $k = r = 1$, $a = \beta = 2$, and $g = h = 10$. Based on equations (10.5) and (10.6), equilibrium military stocks are $(M_A^* = 10, M_B^* = 10)$. Figure 10.4(a) shows the determination of equilibrium graphically using the reaction functions of equations (10.3) and (10.4). Since $(k/a)(r/\beta) = 1/4 < 1$, the players are not overly sensitive to rival military stocks, and the equilibrium at point e is stable. Hence, an

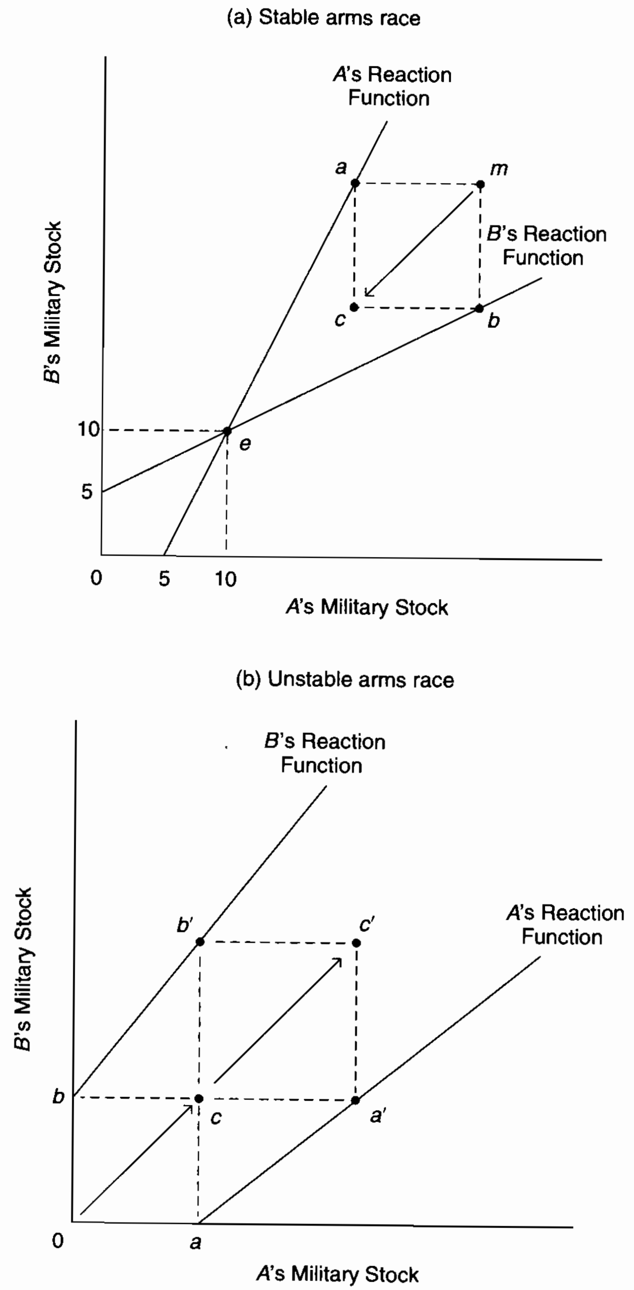

Figure 10.4. Richardson arms race model.

upward shift in military stocks to a point above the equilibrium, like m, causes military stocks to move back toward the equilibrium, as governed by the reaction functions. At point m, player A prefers to move to point a, and player B prefers to move to point b. Both moves taken together imply that the military stocks arrive at point c. From there the process repeats itself, and eventually, military stocks arrive back at equilibrium point e.

Assume now that $k = r = 4$, with all other parameter values remaining the same. Mathematically, equilibrium military stocks become negative, which is not meaningful in an armaments context. What is meaningful, however, is that the relatively large reaction coefficients cause the slope terms on the reaction functions in equations (10.3) and (10.4) to become large. Now each player reacts more strongly to the military stock of its rival. In Figure 10.4(b), the reaction functions imply an escalation of military stocks. Beginning from the origin of zero military stock for each player, A prefers to move to point a, and B prefers to move to point b. Both moves taken together imply that military stocks arrive at point c. In the next round, A increases its military stock to a', while B does the same to b', bringing the joint weapons point to c'. Note that the increases in military armaments in the second round are greater than in the first. Subsequent rounds will depict ever-increasing armaments for each side, reflecting a runaway arms race when $(k/a)(r/\beta) > 1$.

10.4. The Intriligator-Brito Model

Richardson focused on the accumulation of weapons in an arms rivalry under the assumption that the reaction, fatigue, and grievance parameters were constant. Hence, Richardson ignored strategic elements such as the deterrent or attack capability of accumulated weapons that might affect the degree of reactivity of each player to its rival. In an influential model developed in a Cold War context, Intriligator and Brito (I-B) focused on the deterrence and attack implications of two nations' missile stocks M_A and M_B. Here we present a simplified version of the I-B model drawing from Intriligator and Brito (1986) and Wolfson (1985).

Deterrence and Attack Conditions

Consider first how a nation can deter an attack by its rival. Suppose nation A's military planners are concerned that rival nation B might launch an all-out attack to destroy some or all of A's missile forces. In an all-out counterforce (military against military) attack by B, assume that $f_B M_B$ of A's missiles would be destroyed, where the parameter f_B is the number of A's missiles destroyed per counterforce missile launched by B. With any surviving missiles, A could then launch a countervalue (military against civilian) strike against B. Assume A believes there exists for B an unacceptable level of casualties denoted $\bar{C}_B$, such that if A credibly threatens that level of casualties in retaliation, then B will be deterred from initiating the attack. Let v_A be the number of casualties in B caused per countervalue missile fired by A in retaliation. Then the number of surviving missiles that A believes it needs to deter B is $\bar{C}_B/v_A$. Putting this together, if A's missile stock is at least equal to $f_B M_B$ (the number of its own missiles that would be destroyed by an attack) plus $\bar{C}_B/v_A$ (the number of missiles required to retaliate), then A believes it can successfully deter B from attacking. Applying similar logic to B's deterrence of A leads to the following deterrence conditions for nations A and B:

$$M_A \geq f_B M_B + \bar{C}_B/v_A \tag{10.7}$$

$$M_B \geq f_A M_A + \bar{C}_A/v_B. \tag{10.8}$$

Now consider how each nation can successfully attack its rival. Let $\hat{C}_A$ be the maximum casualties that A is willing to sustain if B retaliates to an attack by A, and let v_B be the number of casualties suffered by A per countervalue missile launched by B. In an all-out counterforce attack by A, $f_A M_A$ of B's missiles would be destroyed, leaving $M_B - f_A M_A$ missiles with which B could retaliate and thereby cause $(M_B - f_A M_A)v_B$ casualties in A. If such casualties are no more than $\hat{C}_A$, then A can successfully attack. Applying similar logic to B's attack potential leads to the following attack conditions for A and B:

$$(M_B - f_A M_A)v_B \leq \hat{C}_A \text{ or equivalently} \quad M_A \geq (M_B/f_A) - (\hat{C}_A/f_A v_B) \tag{10.9}$$

$$(M_A - f_B M_B)v_A \leq \hat{C}_B \text{ or equivalently} \quad M_B \geq (M_A/f_B) - (\hat{C}_B/f_B v_A). \tag{10.10}$$

Figure 10.5 shows graphically the deterrence and attack conditions (10.7)–(10.10) of the I-B model. It is important to understand that in the later writings of Intriligator and Brito conditions (10.7)–(10.10) do not model or specify the number of weapons that A and B will choose to accumulate. Rather, the conditions expose various strategic implications

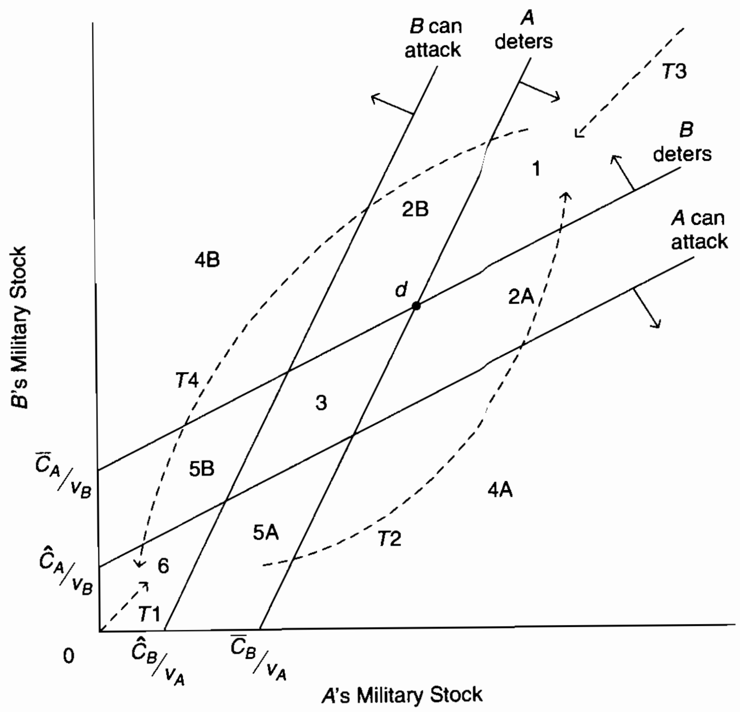

Figure 10.5. Intriligator-Brito model (adapted from Intriligator 1975, p. 349).

for alternative military stocks that A and B might accumulate. Combinations of M_A and M_B on or to the right of the "A deters" line (regions 1, 2A, and 4A) are missile holdings for which A believes it can deter B, while combinations on or above the "B deters" line (regions 1, 2B, and 4B) are those for which B believes it can deter A. Formed at the upper right is an area known as the cone of mutual deterrence (region 1), with d representing a point of minimum mutual deterrence. Combinations of M_A and M_B on or to the right of the "A can attack" line (regions 4A, 5A, and 6) imply that A can successfully attack B, while points on or above the "B can attack" line (regions 4B, 5B, and 6) imply that B can successfully attack A. In the region of jittery deterrence (region 3), A and B can neither attack nor deter. Areas 5A, 5B, and 6 are regions of war initiation. In regions 5A and 5B one side can attack and neither can deter. Region 6 is particularly dangerous because it represents weapons holdings such that each side can attack and neither can deter.

The I–B model can be used to explore the effects of increases or decreases in weapons on the risk of war (Intriligator and Brito 1986).

Beginning from the origin in Figure 10.5, trajectory *T1* is an arms rivalry that moves the nations' weapons holdings into region 6. Because each nation can successfully attack and neither believes it can deter, each nation has an incentive to attack before its rival does, and the likelihood of war is high. Arms rivalry *T1* is consistent with Richardson's view that an arms rivalry increases the risk of war. But Richardson's view is not the only one that emerges in the I–B model. Suppose trajectory *T2* occurs, which according to Intriligator and Brito is roughly descriptive of the first few decades of the Cold War rivalry between the United States and the USSR. Trajectory *T2* pushes the weapons holdings into region 1, where each nation believes it can deter. An increase in weapons into region 1 thus lowers the risk of war, contrary to Richardson's view. At the same time, damage should war come and the cost of military preparation are both higher along *T2*, suggesting that trade-offs among the several goals of arms control exist for some trajectories.

The effects of arms reduction on the risk of war can also be considered in the I-B model. Trajectory *T3* moves the nations' weapons holdings further down in the cone of mutual deterrence, implying less damage should war come and lower costs of military preparation, but no increase in the risk of war. In this case, two of the three goals of arms control are promoted without attenuation of the third. Trajectory *T4* leads to a different result, however. A substantial reduction in weapons moves the nations' holdings into the dangerous region 6 where the risk of war is high. Note also that arms reduction trajectories *T3* and *T4* are implicitly assumed to be costless. In reality, destroying weapons and enforcing arms control treaties can be costly, which tends to reduce the peace dividend available from arms control. As just one example, according to the James Martin Center for Nonproliferation Studies, Japan estimates that the dismantlement and cleanup costs of removing the chemical weapons it left in China after World War II are in the neighborhood of $1.6 billion.

Applications

Iranian Nuclear Weapons Proliferation

At the time of this writing, numerous states have imposed economic sanctions against Iran because of its uranium enrichment and reprocessing programs. Currently, there is uncertainty about whether Iran will attempt to acquire nuclear weapons in the future. Here we restrict our attention to a potential nuclear rivalry between Israel and Iran, should the latter come

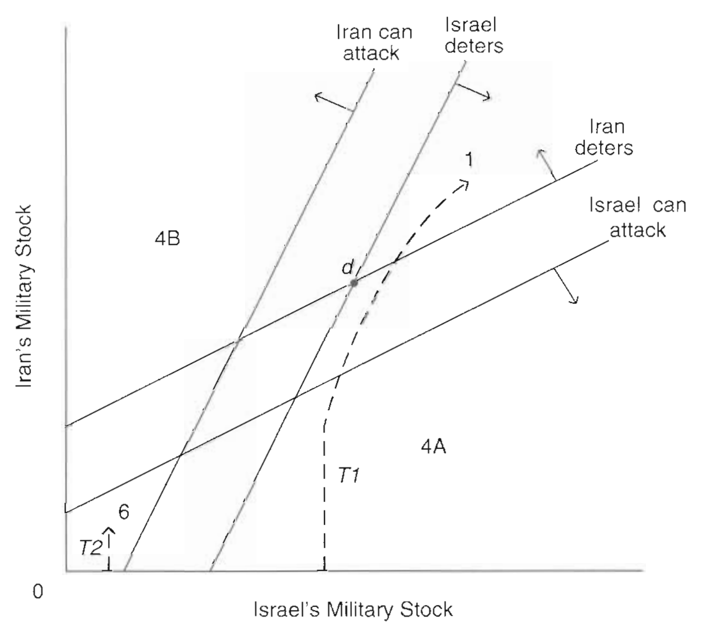

Figure 10.6. Iranian nuclear weapons proliferation in the Intriligator-Brito model.

to possess nuclear weapons. In Figure 10.6, Iranian acquisition of nuclear weapons is represented by an arms trajectory that emerges from the horizontal axis. Of the many possible proliferation trajectories that could occur, two are shown in the figure. Proliferation trajectory *T1* assumes that Israel is already well-stocked with nuclear weapons (see Table 10.2), that Iran begins to accumulate nuclear weapons, and that a nuclear arms rivalry occurs between Israel and Iran. It is conceivable that such an arms rivalry could move into a cone of mutual deterrence (region 1), but not before passing through region 4A where Israel can attack. Whereas trajectory *T1* is potentially dangerous, trajectory *T2* is particularly disconcerting. For this trajectory, the weapons holdings move into region 6, where each country can attack and believes it cannot deter. The I-B model by itself cannot determine whether trajectory *T1*, *T2*, or some other trajectory might better reflect the strategic implications of Iranian nuclear proliferation vis-à-vis Israel. It does indicate, however, that a move toward deployment of nuclear weapons by Iran has the potential to raise the risk of war between Iran and Israel.

Antiballistic Missile Technology in Europe

Although developed for a Cold War context, the I–B model can be used to explore numerous present and future scenarios where weapons

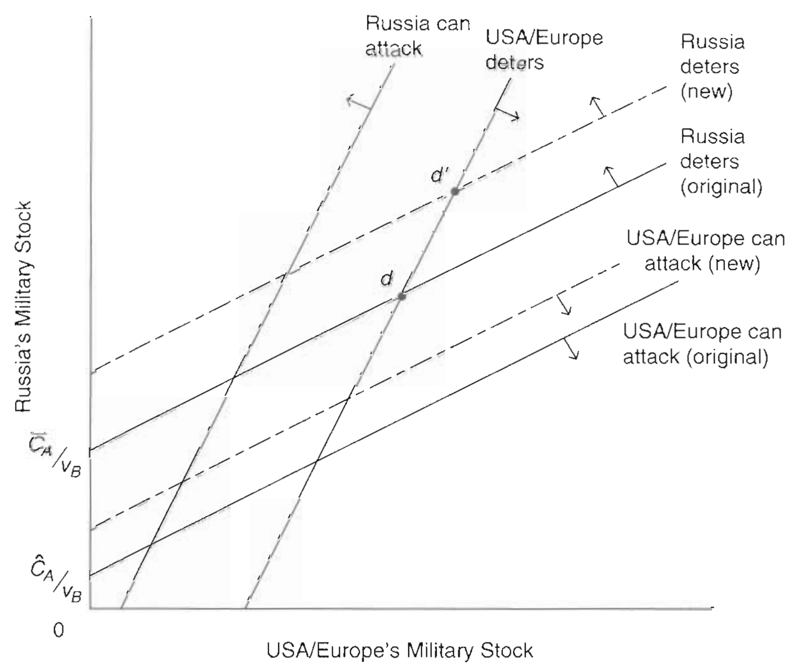

Figure 10.7. One-sided antiballistic missile defense in the Intriligator-Brito model.

effectiveness (f_i and v_i) or acceptable casualties ($\bar{C}_i$ and $\hat{C}_i$) change among arms rivals. For example, at the time of this writing the United States and some of its European allies are considering deployment of antiballistic missile (ABM) defense technology in Europe to protect cities against possible future missile threats from nations such as Iran. In 2007, Russia suspended its participation in the Conventional Forces in Europe Treaty in protest over the ABM deployment. Figure 10.7 provides possible insight into Russia's opposition to the ABM technology. Let nation *A* be the United States and its European allies and nation *B* be Russia. The deployment of an ABM system in Europe to protect cities from an accidental or purposeful missile strike from a third party also lowers the countervalue effectiveness v_B of Russia's missiles. This shifts the "Russia deters" and "USA/Europe can attack" lines upward in Figure 10.7, so that the USA/Europe's attack capability is expanded at the same time that Russia's deterrent capability is undermined. This prospective change in relative capabilities helps explain the strong opposition by Russia, which claims that deployment of ABM technologies in Europe would undermine regional stability.

Inherent Propensity toward War in the I-B Model

In Chapter 9 we explored Thomas Schelling's (1966, ch. 6) idea that certain configurations of military technology, geography, and military organization could imply a first-mover advantage in war. Such an "inherent propensity toward war," to use Schelling's phrase, is shown in the I-B model by region 6 of Figure 10.5, where each side can attack the other and neither can deter. A more pervasive form of incentive for mutual attack arises when the model's usual counterforce effectiveness assumptions are altered so that region 1, the cone of mutual deterrence, is eliminated.

To demonstrate this point, we rely on the fact that the cone exists only when the product of the counterforce effectiveness terms is less than one, that is, when $f_A f_B < 1$ (Wolfson 1987, p. 293). As a way of illustration, we begin with the usual assumption that the condition for the cone is satisfied. Suppose, for simplicity that f_A and f_B are both less than one. As indicated by equations (10.7) and (10.8), the slopes of the "*A* deters" and "*B* deters" lines in Figure 10.5 are $1/f_B$ and f_A, respectively. This means that when $f_B < 1$ and $f_A < 1$, the "*A* deters" line is steeper than the "*B* deters" line, so that a cone of mutual deterrence arises, as depicted by region 1 in Figure 10.5. Intuitively, when military technology is such that one missile in a counterforce attack destroys less than one rival missile, then attack effectiveness is relatively low and mutual deterrence is possible.

Now assume that attack effectiveness for each player is high so that the condition for the cone is not satisfied, that is, so that $f_A f_B > 1$. For example, suppose that f_A and f_B are each greater than one, such that one missile in a counterforce attack can destroy more than one rival missile. In this case the "*A* deters" line is flatter than the "*B* deters" line, and as a consequence no cone of mutual deterrence exists. This result of high attack effectiveness is depicted in Figure 10.8. With the disappearance of the cone, notice that region 6, the area of mutual attack, now occupies a substantial portion of the graph. Whereas the customary Figure 10.5 predicts that relatively high and roughly balanced missile stocks imply mutual deterrence and a low risk of war, Figure 10.8 suggests that such missile holdings can be associated with a dangerous inherent propensity toward war.

The possibility of an inherent propensity toward war in the context of weapons of mass destruction cannot be precluded. Based on MIRV technology, for example, one missile can contain multiple independently targetable warheads. The United States' MX missile, for example, can hold up to 10 independently targetable warheads. Hence, it is technologically feasible for a missile to have a counterforce effectiveness term greater than one. Negotiated reductions in multiple warhead missiles by the United States and Russia have been partly motivated by concerns over the first-strike potential of such weapons. We saw in Chapter 9 how fleets of fast and deep-strike military aircraft may have contributed to an inherent propensity toward war between Egypt and Israel in 1967. Imagine a future nuclear weapons rivalry between Israel and Iran wherein aircraft are a primary delivery platform and each aircraft contains multiple warheads. In such a scenario, the risk of nuclear war could be unusually high. The militarization of space discussed in Chapter 9 also suggests the potential for "futuristic" technologies to generate an inherent propensity toward war. For example, suppose two nuclear rivals each deploy a sophisticated array of satellites designed to detect and target enemy missile sites and to shoot down incoming missiles with satellite-based laser technologies. If such technologies could be made effective against fast-moving missiles, it is reasonable to believe that the same technologies could be used to destroy the slow-moving satellites of a rival, thus conveying a first-mover advantage in war.

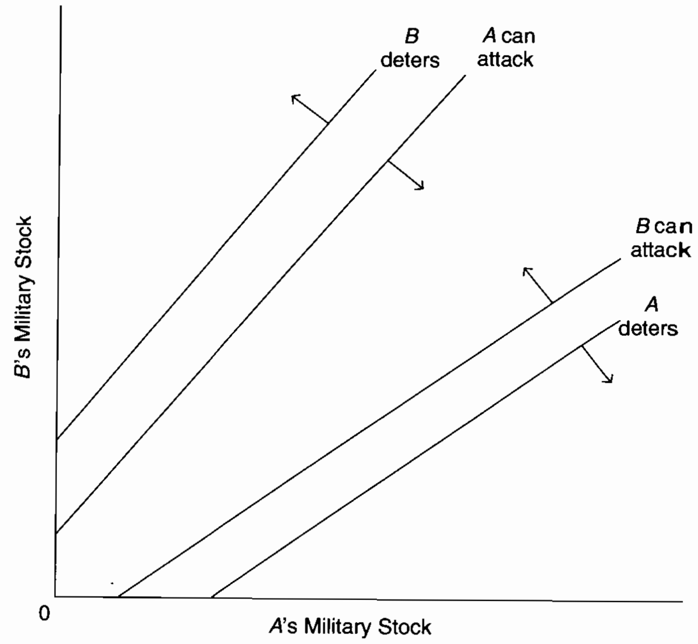

Figure 10.8. Inherent propensity toward war with high attack effectiveness.

10.5. An Economic Choice Model of Arms Rivalry

Optimal Allocation of Resources to Military and Civilian Goods

We turn now to a rational choice model of arms rivalry due originally to Anderton (1990). As earlier, there exist two rivals *A* and *B*, who may be nations or non-state groups. Player *A*'s choice problem is to allocate its resources between military output M_A and a composite civilian good Y_A so as to maximize utility, where utility is a function of *A*'s composite good and level of security S_A. Because the two players are rivals, *A*'s security can be written generally as $S_A(M_A, M_B)$, with the assumption that its security increases with its own military output M_A but decreases with its rival's output M_B. Player *B* faces an analogous choice problem.

In Figure 10.9 we depict *A*'s choice problem in a four-quadrant diagram, where all variables are measured positively as distances from the origin. Quadrant II, at the upper left, shows *A*'s production possibilities frontier (PPF) for alternative combinations of military and civilian outputs M_A and Y_A. Quadrant III simply plots a 45-degree line, which serves to project *A*'s military output from quadrant II into quadrant IV. Quadrant IV graphs *A*'s security function, which shows *A*'s level of security for alternative stocks of military output, holding *B*'s military output M_B constant. These three quadrants systematically join various levels of civilian output Y_A with corresponding levels of security S_A, thereby generating in quadrant I a civilian-security possibilities frontier (CSPF). Included also in quadrant I are *A*'s indifference curves, representing *A*'s utility function defined over alternative combinations of civilian output and security. Geometrically, *A*'s choice problem is to choose a feasible combination of civilian output and military output (and hence security) so as to reach the highest indifference curve along the CSPF, taking as given the military output of player *B*.

To understand Figure 10.9, assume initially that the military output of rival *B* is M_B^0, thus generating the higher security line $S_A(M_A, M_B^0)$ shown in quadrant IV. This security line together with the PPF in quadrant II combine in quadrant I to generate the CSPF labeled *HN*. Given M_B^0, player *A* maximizes its utility at optimum C^0 by producing outputs M_A^0 and Y_A^0, thereby enjoying the security benefit S_A^0 of its military output and the consumption benefit of its composite good. Now suppose that player *B* increases its military output to M_B^1. Because *B* is a rival, player *A* suffers a decrease in security, other things equal, causing its security function to rotate downward to $S_A(M_A, M_B^1)$. Owing to the linkages in the model, the

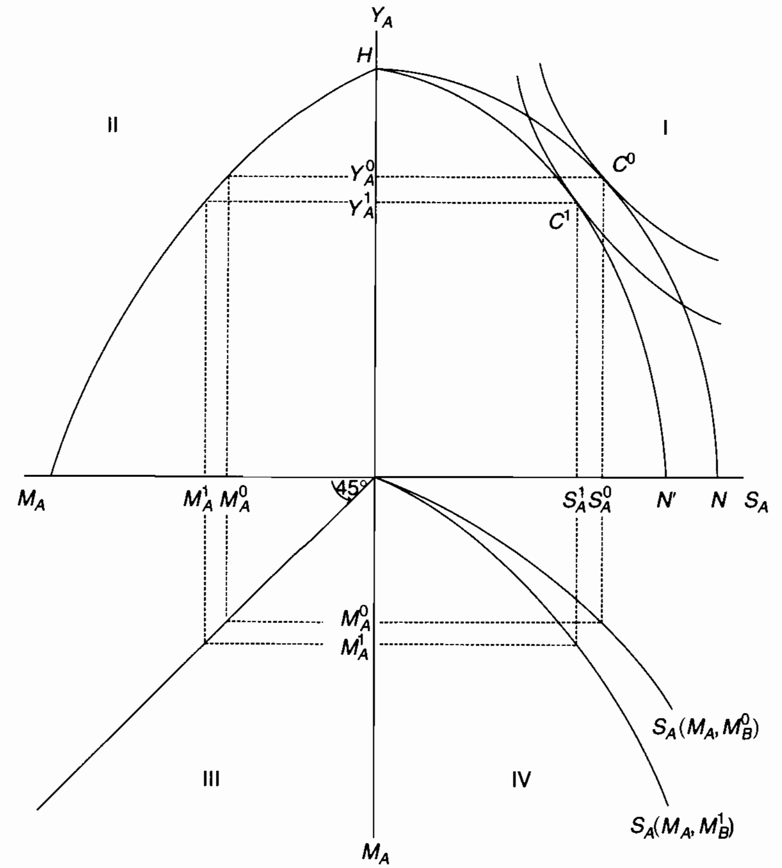

Figure 10.9. Player *A*'s optimal allocation of resources to civilian and military goods (adapted from Anderton 1990, p. 152).

CSPF in turn rotates downward to *HN*'. As a consequence, *A* is motivated to reallocate its resources until it achieves optimum C^1, with military output M_A^1, civilian good Y_A^1, and security S_A^1. Notice that player *A* reacts to *B*'s increase in military output with an increase of its own, a point to which we will return.

Two broad themes emerge from Figure 10.9. First, economic and security variables are inextricably linked. The point at which a player operates on its production possibilities frontier in quadrant II is governed in part by security considerations. Moreover, the level of security a player is able to achieve is influenced by the economic capacity available to the player. Second, the figure reflects the multidisciplinary nature of modeling

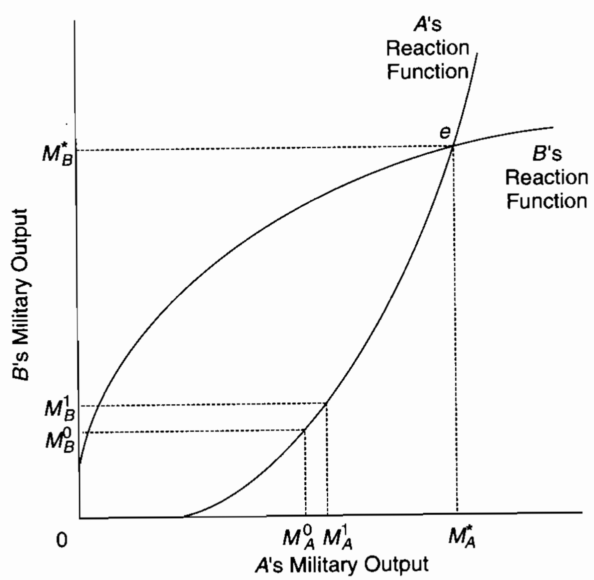

Figure 10.10. Arms rivalry equilibrium in the economic choice model.

a player's resource allocation decision. Quadrant II reflects the supply side of the model, a traditional domain of economics. Quadrant IV involves security issues, which are emphasized in international relations. The preferences of a group over Y and S in quadrant I are shaped by various people within the group and by the institutions that govern the group's collective actions. Hence, preference formation belongs in the domains of political science and public choice.

Reaction Functions and Arms Rivalry Equilibrium

As already noted, the rivalrous nature of *A*'s and *B*'s relationship induces player *A* to respond to increases in *B*'s military output with increases of its own. This principle is formally represented in Figure 10.10 by *A*'s reaction function, which shows *A*'s optimal military output for any given military output by *B*. We have already derived two points on *A*'s reaction function in Figure 10.9: if *B* produces M_B^0, *A*'s best reply is M_A^0, and if *B* produces M_B^1, *A*'s best reply is M_A^1. Additional points on *A*'s reaction function are derived by repeating the exercise in Figure 10.9 for various other outputs by *B*. In an analogous manner, working again through a four-quadrant analysis generates *B*'s reaction function, also shown in Figure 10.10.

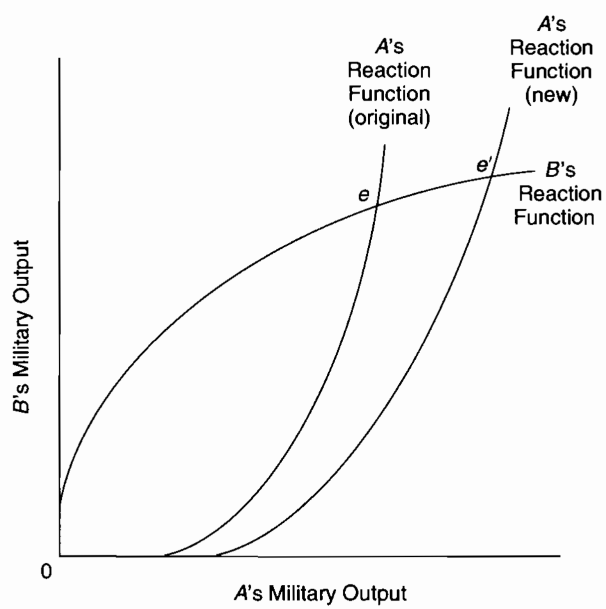

Figure 10.11. Effect of economic growth in *A* on arms rivalry equilibrium.

A Nash equilibrium exists when each rival's military output is a best reply to the other's. Geometrically, this means that an equilibrium is determined in Figure 10.10 at point *e*, where the two reaction functions intersect. Thus, in equilibrium, *A* chooses output M_A^*, which is a best reply to *B*'s M_B^*, at the same time that *B* chooses M_B^*, which is a best reply to *A*'s M_A^*. Because the reaction functions are generated from each player's four-quadrant model, the equilibrium in Figure 10.10 is equivalent to the simultaneous solution of the players' economic choice problems.

Applications

Economic Strength and Arms Rivalry Competitiveness

The position and curvature of a player's reaction function are determined by the several components of the economic choice model from which the reaction function is derived. One of these components is the production possibilities frontier, which reflects the economic capacity of a player to react to an arms rival by producing weapons of its own. In Figure 10.11 we show how the arms equilibrium moves from *e* to *e′* when player *A* experiences economic growth but player *B*'s economy is unchanged. In *A*'s four-quadrant model, economic growth pushes outward the PPF in quadrant II, thus expanding A's CSPF in quadrant I (not shown). Player A finds that economic growth allows it to expand its military and civilian production, holding B's military output constant. Hence, A's reaction function shifts outward, indicating an increased demand for military output. This shift sets off new rounds of action and reaction between A and B until a new equilibrium emerges at point e' in the figure. Note that A's military output increases substantially more than does B's, which is plausible because A's economic strength has expanded while B's is unchanged. As an illustration of the process depicted in Figure 10.11, some scholars maintain that economic stagnation in the Soviet Union during the 1980s made it increasingly difficult for the Soviets to maintain competitiveness in its Cold War rivalry with the United States (Wolfson 1985).

Arms Control

An arms rivalry generates a security dilemma, wherein each player's attempt to improve its security by increasing its own weapons causes the rival to respond by also increasing weapons, which in turn reduces the original player's security. This dilemma provides a basic rationale for arms control, namely, that a mutual reduction in weapons can save resources without sacrificing security.

We demonstrate this rationale for arms control with Figure 10.12, which is similar to Figure 10.10 but is more complete and thus more intricate. Recall in the earlier model that player A's utility is a function of its civilian output Y_A and its security S_A. With a little work, this function can be translated mathematically into a utility function defined in terms of both players' military outputs M_A and M_B. Without getting formal, the key is to recognize that A's PPF implicitly defines Y_A as a function of M_A, and its security function explicitly defines S_A as a function of M_A and M_B. Consequently, player A's PPF and security function can be substituted into its utility function, thereby resulting in a translated utility function written generally as $U_A(M_A, M_B)$. As usual, this utility function can be represented with indifference curves, but the behavior of the indifference curves needs some explanation.

Of A's many indifference curves in Figure 10.12, we have drawn just one, that being the curve passing through the Nash equilibrium point e. Because e lies on A's reaction function, we know that A's military output at that point is A's best output, given the corresponding military output of B. Player A could be equally satisfied with less military output, but only if A was compensated for its lost security by an appropriately reduced level of military output by B. Thus, A's indifference curve must fall off to the left of

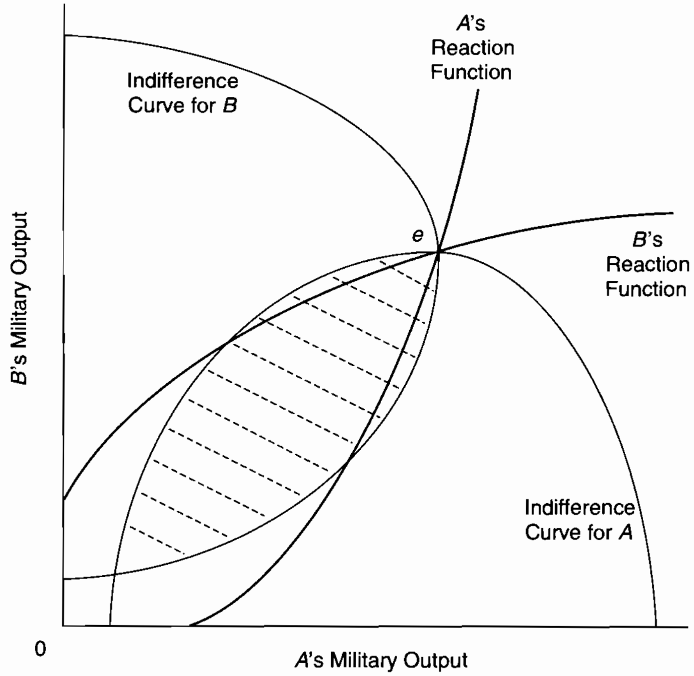

Figure 10.12. Arms control in the economic choice model.

e, as shown. Going the other direction, A could be equally satisfied with more military output, but only if A was compensated for its forgone civilian output, once again, by an appropriately reduced military output by B. Thus, A's indifference curve must also fall off to the right of e. Repeating the logic for other points along A's reaction function means that A's indifference curves are positively sloped to the left of A's reaction curve and negatively sloped to the right. Notice also that because unilateral reductions in B's military output M_B leave player A better off, points on lower indifference curves are more preferred by A.

Similar reasoning applies to player B, whose original utility function can be translated into a function written generally as $U_B(M_B, M_A)$. The translated function can then be represented by indifference curves, one of which is drawn for B passing through point e. As shown, B's indifference curves are negatively sloped above B's reaction function and positively sloped below it, and points on indifference curves to the left are more preferred by B.

With the properties of A's and B's indifference curves in mind, we can illustrate the basic rationale for arms control using Figure 10.12. Notice that the two indifference curves drawn through equilibrium point e form a highlighted lens-shaped area. Points within the lens lie below A's indifference curve through e and hence are preferred to e by A; they also lie to the left of B's indifference curve through e and hence are preferred to e by B. Therefore, the lens-shaped area forms the region of mutual gain, wherein at least one player is better off and neither is worse off relative to the equilibrium e. This means in principle that the players should be able to negotiate an arms control agreement whereby they both benefit by reducing their weapons levels to some specified point within the lens. The immediate qualification to this statement, however, is that each player will have an incentive to cheat on the agreed arms control point by unilaterally increasing its weapons output toward its reaction function, thereby increasing its utility. This incentive explains why many arms control agreements contain formal inspection and verification protocols to guard against cheating.

Arms rivalry and arms control reflect Schelling's (1960, pp. 4–6) central thesis that conflict often involves mutual dependence alongside of opposition, and that for this reason many conflicts are essentially bargaining situations. In Figure 10.12 the players have an incentive to mutually reduce armaments, despite their hostility toward one another. By jointly reducing weapons outputs from point e into the region of mutual gain, the players can keep their security levels roughly the same while freeing up resources to produce civilian goods, thus increasing overall utility. Note that a mutual reduction supports Schelling and Halperin's second and third goals for arms control: since weapons stocks are lower, damage is decreased should war come, and the cost of military preparation is lowered. Figure 10.12 does not by itself address Schelling and Halperin's first arms control objective, namely, reduction in the risk of war. In Richardson's view, lower weapons stocks would reduce the risk of war. In the Intriligator-Brito model, however, if weapons stocks are so low that a region of mutual attack is reached, the risk of war could be high.

There are a number of important factors that might offset the resource savings generated by arms control. For example, inspection and verification procedures are not costless, and efforts to dismantle or destroy weapons can be quite costly, as the Cooperative Threat Reduction Program explicitly recognizes. Moreover, the substitution principle reminds us that efforts to restrain one form of activity can lead to substitutions into other activities. If the weapons class controlled in Figure 10.12 is, for example, long-range missiles (as in the SALT treaties), the players might expand their production of nuclear warheads. Alternatively, if missiles and warheads are controlled, the players might increase the quantity or

technological sophistication of their conventional weapons. In intrastate arms rivalries, if rebel leaders lose access to land mines, they might recruit additional personnel and arm them with assault rifles (see Chapter 3). As Schelling and Halperin (1961, p. 120) noted: "[I]t is by no means obvious that arms control, even rather comprehensive arms control, would entail rapid and substantial reductions in military outlays . . . . It is quite possible that arms control would increase them." Surprisingly, there have been few formal empirical studies of the resource cost or the substitution possibilities associated with arms control agreements. One exception is Craft (2000), who finds empirical evidence that the Washington Naval Agreements of the 1920s between the United States, the United Kingdom, and Japan provided resource savings for a limited time period, followed by greater expenditures to promote new naval technologies.

10.6. Selected Empirical Studies

Structure of Arms Rivalries

A large number of studies have attempted to estimate Richardson-type arms models, but they have tended to yield reaction coefficients that are statistically insignificant, incorrectly signed, or exceedingly fragile. Reviewing the literature, Dunne and Smith (2007) argue that changing technologies and environments mean that the action-reaction relationships among arms rivals are probably too unstable to support the usual time-series analysis. They express optimism, however, that studies employing panel or cross-section methods might provide useful estimates of average interaction effects.

An example of such a study comes from Collier and Hoeffler (2007b), who estimate a military expenditures model based on a dataset spanning 161 countries over the period 1960 to 1999. Observations are country averages computed over five-year periods 1960–64, 1965–69, . . ., and 1995–99. The dependent variable is the logarithm of (average) defense burden, where defense burden is equal to military expenditure as a percentage of GDP. The key right-hand variable for our purposes is the lagged logarithm of a measure of the defense burden of neighboring countries. Other independent variables include measures for current interstate war, past interstate war, current civil war, risk of civil war, foreign aid, income, population, democracy, post–Cold War period, and Israel.

Collier and Hoeffler's (2007b) results are methodologically encouraging and substantively interesting. The estimated coefficients on the various control variables are as might be expected: war and the risk of war lower security and hence generate increased military spending; increased population tends to decrease the defense burden, suggesting economies of scale in the production of security (see Chapter 9); foreign aid increases military spending, reflecting the fungibility of foreign financial assistance (see Chapter 3); and defense burdens are lower in democracies and after the Cold War. On the issue of arms rivalry, Collier and Hoeffler estimate the reaction coefficient for neighbors' military spending to be 0.10. This means that if a country's neighbor increases military spending by 10 percent, then the country on average will react by increasing its own spending by one percent. This action and reaction between the country and its neighbor then sets up a multiplier effect that further increases spending in equilibrium. As one example, Collier and Hoeffler (2007b, p. 16) estimate that if the risk of civil war increases generally by 10 percentage points across a region, then each country within the region will increase military spending immediately by 7.3 percent and eventually by 8.1 percent after all actions and reactions are completed.

Arms Rivalry and the Risk of War

Based on studies of military expenditures prior to World Wars I and II, Richardson (1939, 1960a) believed that arms rivalries increased the risk of war. In the 1970s, introduction of the Intriligator-Brito model raised questions about the generality of Richardson's view. Recall that some arms rivalry trajectories (e.g., *T1* in Figure 10.5) are associated with a greater risk of war while others (e.g., *T2* in Figure 10.5) can be associated with a lower risk. Wallace (1979) was the first to empirically test the issue, and he found that arms rivalries between major powers had a strong positive effect on the escalation of militarized disputes to war. Diehl (1983) and others questioned Wallace's results in subsequent studies.

Building on this earlier literature, Sample (2002) investigates the effect of military buildups on the risk of war based on data for militarized interstate disputes (MIDs). Recall that a MID is a "threat, display or use of military force short of war by one member state . . . explicitly directed towards the government, official representatives, official forces, property, or territory of another state" (Jones et al. 1996, p. 168). Sample's study spans the period 1816–1992 and covers 2,304 dispute dyads, of which 267 involved major states, 1,196 involved minor states, and 841 involved a major and a minor state. The dependent variable in her regression is an indicator for whether a MID escalated to war. Her key right-hand variable measures whether both nations in the dyad were involved in rapid military buildups. Other right-hand variables control for nuclear capability, the presence of a territorial dispute, contiguity, comparative military capabilities, and high defense burdens.

Sample's statistical results for her full sample show a significant positive relationship between military buildups and escalation to war. Disputes involving dyads with rapid buildups are estimated to be more than twice as likely to escalate to war, other things equal. Sample also finds that the presence of nuclear weapons lowers the risk of war by about half. When she estimates her model separately for the three types of dyads, she discovers that military buildups increase the risk of war for major power and minor power dyads but not for mixed (major-minor) dyads. If she further restricts her analysis to the post–World War II period, she can discern no significant effect of buildups on the risk of war, but the presence of nuclear weapons continues to reduce the risk of war for major and mixed dyads. According to Sample, rivals in mixed dyads react to each other's buildups differently relative to rivals in major and minor dyads, and countries in general have changed their perception of deterrence since the use of nuclear weapons in World War II.

Determinants of Nuclear Weapons Proliferation

While most analyses of nuclear weapons proliferation have been case studies, Singh and Way (2004) provide a large-sample investigation of risk factors based on the status of states' nuclear weapons research and development programs. They begin by defining four stages of nuclear weapons proliferation, ranging from no interest to serious exploration to program launch to weapons acquisition. For their sample of 154 countries over the period 1945–2000, 23 nations seriously explored nuclear weapons, 16 proceeded to launch programs, and 9 acquired nuclear weapons. Variables for the three active stages of nuclear weapons proliferation are coded for each country in each year and serve as dependent variables. Explanatory variables include income, industrial capacity, external security concerns, political organization, and trade policy. Singh and Way find that external security issues have a powerful effect on a state's interest in nuclear weapons. States that are involved in long-lived rivalries and frequent militarized interstate disputes are at substantially greater risk of moving toward nuclear weapons. Economic development generally has a positive effect on a state's interest in nuclear weapons, but the likelihood of proliferation actually drops off at higher income levels. Singh and Way also show that the more open a state is to trade, the lower the risk of nuclear weapons proliferation.

10.7. Bibliographic Notes

Accessible overviews of data on military expenditures worldwide are provided by Brzoska (1995) and Stockholm International Peace Research Institute (2007, ch. 8). Data and policy articles on WMD proliferation, bilateral and multilateral arms control treaties, and nonproliferation regimes are available from the James Martin Center for Nonproliferation Studies (http://cns.miis.edu/). The Norwegian Initiative on Small Arms Transfers (www.nisat.org) and the Graduate Institute of International Studies (Geneva) Small Arms Survey (www.smallarmssurvey.org) offer data and policy articles on the production and trade of small arms and light weapons (SALW). Brauer (2007) provides an excellent survey of data and models on the production and trade of MCW, SALW, and WMD.

Cirincione, Wolfsthal, and Rajkumar (2005) present an in-depth overview of nuclear, biological, and chemical weapons proliferation. Langford's (2004) analysis of biological, chemical, and radiological weapons materials and technologies can be helpful to health professionals, emergency responders, and the media. Guillemin (2005) provides a compact summary of the history of biological weapons and suggests ways to curtail their spread, while Schelling (2006) offers a fascinating interpretation of a "taboo" against the use of nuclear weapons that has emerged among states. The edited volumes of Banks and Castillo-Chavez (2003) and Davis and Schneider (2004) provide numerous articles on biological weapons proliferation and control. Allison (2004) and Howard and Forest (2008) explore the potential for terrorists' use of WMD.

Rapoport (1957) and Hess (1995) offer insightful overviews of Richardson's quantitative approach to war and peace. Boulding's (1962, ch. 2) important extension of the Richardson model generalizes action-reaction processes to numerous forms of hostility and friendliness, not just arms rivalry, and includes applications to states, non-state groups, and individuals. Isard (1988, ch. 2) and Sandler and Hartley (1995, pp. 82–89) review other extensions of the Richardson model.

Brito and Intriligator (1995) provide an accessible overview of the I-B strategic model of arms rivalry. Anderton (1992a) generalizes the I-B model to include alternative assumptions about attack capabilities and counterforce effectiveness. Wolfson (1985) combines the strategic components of the I-B model with resource scarcity inherent in an economic

choice model, which he then applies to the United States' "arms race economic warfare" against the USSR during the Cold War.

McGuire (1965) offers an early economic choice model of arms rivalry that embeds strategic concerns of deterrence and attack in a rational choice framework. His theoretical applications are extensive and include explorations of Cournot-Nash equilibrium, the contract curve available under bilateral arms control, the Stackelberg solution available under unilateral arms control, survival-extinction solutions, and the effects of information (and secrecy) on arms rivalry and arms control. Brito (1972) provides the first dynamic optimization model of arms rivalry. Reviews of theoretical arms race models include Isard (1988), Brito and Intriligator (1995), and Sandler and Hartley (1995). Hammond (1993) provides a historical analysis of interstate arms races occurring over the 1840–1991 time period. Colaresi, Rasler, and Thompson (2007) examine more than 150 interstate strategic rivalries spanning the nineteenth and twentieth centuries and draw important lessons about conflict risk, arms racing, alliance behavior, and relative capability advantages.

The empirical literature on the structure of military buildups in interstate arms rivalries is vast; valuable literature reviews include Brauer (2002) and Dunne and Smith (2007). Geller and Singer (1998, pp. 79–81) and Gibler et al. (2005) provide concise overviews of empirical studies of the relationship between arms rivalry and interstate war. Singer (2007) provides a historical perspective and review of empirical evidence on nuclear proliferation.

Formal theoretical models of arms control inspection and verification are presented by Saaty (1968) and Brams (1985, ch. 4), while Rueckert (1998) provides a nonquantitative overview. Levi and O'Hanlon (2005) offer insightful analysis of past and future arms control and nonproliferation policies. Larsen (2005) provides a dictionary on arms control and disarmament, which includes an extensive bibliography and information on treaties, government and nongovernment organizations, weapons, journals, and Web sites.