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UNIVERSITY OF CALIFORNIA,
IRVINE

Ballistic Missile Proliferation: A Self-Organizing Phenomenon

DISSERTATION

submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSPHY

In Economics

By

Daniel T. Barkley

Dissertation Committee:
Professor Arthur De Vany, Chair
Professor David Brownstone
Professor Martin McGuire
Professor Wayne Sandholtz

2000

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Martin C McGuire

Committee Chair

University of California, Irvine
2000

DEDICATION

TO:

My Parents, The Reverend Ardell M. Barkley Jr. and Sarah F. Barkley

My friends and fellow students who provided me with vital personal support

World Peace

"Throughout history, wars and peaceful interactions might have left the world in a critical state in which conflicts and social unrest spread like avalanches."

-Bak and Chen

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I also would like to acknowledge Dr. Kim Neuhauser, Kathy Alberti, and Iris Adams, whose guidance, support and friendship contributed to my personal growth during my tenure at UCI.

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Dissertation:

Ballistic Missile Proliferation: A Self-Organized Phenomenon
[Abstract Attached]

Areas of Concentration:

A Model of City-size Distribution: Evidence from Cross-country Data.
[Abstract Attached]
Let's Do Launch: Comparative Advantage in Rocket Launchers [Abstract Attached]

Other Research Topics:

Urbanization Economics: The Location of Private Firms in California Counties
[Abstract Attached]
Jail Capacity and Jail Overcrowding in Orange County Jails
[Abstract Attached]

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Professional Experience

Western Digital October 1998 to July 1999
Positions: Business Forecasting & Data Warehousing
Business Forecasting: I developed statistical system that rated the accuracy of Western Digital (WD) customers' (e.g. IBM, Dell, Compaq) sales *forecasts* relative to the *actual* number hard disk drives purchased. This effort involved the application of statistical correlation formulas to forecast sales and actual sales. I also built regression models that predicted sales forecasts.
Data Warehouse Monitor: Monitored usage data mining tools. This involved retrieving statistics from WD's data warehouse with Micro Strategy's Decision Support System Web and Agent tools. I then created charts, tables, and reports documenting weekly and monthly user performance.

National Academy of Sciences: June 1998 to August 1998
Position: Internship
This research investigated the productivity of transportation infrastructure. I collected capital stock, investment, and traffic volume time series (1959 – 1995) for the nation's highways, ports, railroads and inland waterways. I then created charts comparing trends transportation infrastructure and usage. In addition I used econometrics to investigate the causal effects of investments in highway capital stocks and industrial output.

University of California, Irvine: September 1992 to Present
Position: Teaching Assistant
Assisted in the instruction of various macroeconomics, international trade, and statistic courses for undergraduates majoring in social science. Conducted weekly recitation sessions, prepared students for examinations, reviewed homework exercises, discussed reading assignments and performed practice problems.

Orange County Administrative Office: June 1996 to April 1997
Position: Research Assistant
Assisted in writing the *Institutional Overcrowding Report*. This report describes how the demand and use of institutional units results in overcrowding in adult and juvenile facilities. The report provides insights on the number of additional units the County is considering to alleviate jail overcrowding in its adult and juvenile facilities. The also report addresses specific information on adult and juvenile custody facility overcrowding and alternative programs.

University of California, Irvine: May, 1994 to December, 1994
Position: Research Assistant
The research examined the relationship between transportation accessibility and economic activity following the 1994 Northridge earthquake. I helped compile a mail survey to determine the impact the disaster had on the commuting patterns of workers in 2,100 Los Angeles area firms.

University of California, Irvine: May 1995 to September 1995
Position: Research Assistant
In May of 1995, the University of California Transportation Center elected to fund my proposal to examine agglomeration economies, highway capital stock and economic development in 55 California counties between 1970 and 1988. I constructed a time series database consisting of the annual number of business establishment per county, the annual value of highway capital stock and the annual county urbanization level from 1970 to 1988. The model used urbanization economies and highway capital stock to explain over 60% of the variation in the location of private firms throughout California.

General Dynamics Corporation: January 1988 to October 1990
Position: Engineer
I performed structural analysis of ground handling equipment used in the transportation of satellite components and *Atlas* rocket stages. I created finite element models to simulate loading conditions, designed mechanical hardware to accommodate the transportation of satellite and rocket components, and compiled reports documenting the structural capacity of newly designed articles.

Community Service

Graduate and Professional Opportunity Program. Served as a mentor in the Student Ambassador Program. This retention and orientation program matches incoming graduate students with continuing graduate students at UC-Irvine.

Graduate Voice (*GV*). Served as an editor and contributing writer for the *GV*. The *GV* is a quarterly
newsletter which highlights topics and issues of concern to graduate students at UC-Irvine.

1997 California Minority Graduate Education Forum. Served as moderator for panel discussion on how to best prepare for applying to doctoral programs in the Social Sciences.

1997 Summer Bridge Computer Literacy Instructor. Summer Bridge is an academic enrichment program designed to prepare incoming minority freshman for the rigors of college level course work at UC-Irvine.

A Model of City-size Distribution: Evidence from Cross-country Data

Replication Paper

Much of the literature on city-size distribution has focused on investigating how city size distributions conform to the Pareto distribution. Numerous studies have shown that city-size distributions, across countries and over time, conform to the Pareto distribution. It is further believed that the Pareto coefficient, which varies considerably among countries, is a relatively accurate measure of population concentration. Subsequent research has empirically demonstrated that city sizes conform remarkably well to the Pareto distribution and that the Pareto exponent can serve as a concise measure of population concentration.

Utilizing data from magnetic files of the World Bank, Gershon Alperovich (1993) investigated the relevancy of a set of descriptive variables in explaining systematic variations in city-size distributions among countries. He found that populations tended to be more evenly distributed among countries with relatively high income per capita; populations tended to be less evenly spread among cities where government's involvement in the economy is profound; and that scale economies promoted urban concentration.

This paper is an effort to replicate the empirical results Alperovich found in his investigation of city-size distributions. This paper builds upon the original analysis by introducing more explanatory variables, which help to explain up to 56% of the variation in the Pareto exponent across countries. My replication paper corroborates many of Alperovich's findings. This paper provides new insights on factors that impact how cities are distributed across countries. In addition to confirming some of Alperovich's original results, my investigation found that income inequality, productivity per worker, ethnic composition, population, and level of urbanization to be significant determinants of city size distribution.

African Monetary Conversion: A Proposal for African Economic Development

Abstract

Abuja Treaty, ratified by 51 African Heads of State at an Extraordinary meeting in 1991, calls on member-states to create an "African Economic Community" by the year 2025. Integration is seen as means to further economic development through unification.

Modern economic development requires the use of a wide array of natural resources and diversified production. Individually, African states cannot establish large-scale productive complexes because their markets are far too small. In terms of population, 22 sub-Saharan countries have populations of five million or fewer, and eleven have populations under one million (Ndegwa, 1985). This issue becomes particularly important if it is recalled that successful economic integration in the developed countries is built on highly developed industrial structures (Orimalade & Ubogu, 1984).

The task of economically uniting Africa is a formidable challenge that can not be achieved in any meaningful fashion without monetary convertibility. Presently however, over 20 different kinds of currencies are used in Africa; many of which are not directly interchangeable. The Abuja Declaration of 1991 constituted a major step toward the creation of a continental exchange rate mechanism, yet it did not outline any specific monetary strategy. This research addresses the issue of currency convertibility by proposing an exchange rate mechanism whereby the currencies of African nations are pegged to a weighted average of gold, platinum, silver, copper, and nickel. I have entitled this denomination the "Continental Unit of Exchange"(CUE). I analytically determined the CUE's composition by calculating the combination of minerals that simultaneously yield the maximum value per unit and minimum price variance over time (1972-1988). I solved this optimization problem by constructing a linear programming model.

Once I determined the optimal proportion of minerals in one CUE, I then calculated its past annual values (1972-1988). The price histories of the CUE enabled me to calculate the optimum level of foreign reserves as well as a country-by-country bilateral exchange rate vis-a-vis the CUE. I estimated the optimal level of foreign exchange reserves, R and CUE reserves for each country with a linear programming function that minimized the opportunity cost (r^*R and r^*CUE where r is the country's discount rate) of holding both kinds of reserves subject to the constraint that each country maintained sufficient reserves to purchase imports (1972-1988). Finally, I set the monetary translations between each national currency and the CUE to the time series regression coefficient that resulted from an ordinary least squares regression of the national currency on the CUE.

Capacity & Overcrowding in Orange County Jails

Abstract

The crowding of correctional facilities is one the criminal justice system's most serious problems. Institutional overcrowding not only endangers the lives of inmates, and the administrators of the associated detention facilities, it may also endanger the public through early release of potentially dangerous offenders. Conventional research on the causes of jail overcrowding typically attributes the problem to forces exogenous to the criminal justice system: population growth, increases in rates of crime, and anti-crime legislation. While these factors are seemingly related to jail congestion, they do not convincingly explain the long-run growth in the average number of inmates annually housed over capacity in Orange County, California. Accordingly, this project turns its attention to examining how forces *within* the criminal justice system might be responsible for institutional overcrowding.

Specifically, I investigate the precedence of jail capacity and institutional overcrowding using a standard time series regression technique known as the *Granger test for causality*. The Granger approach does not test for causation per se but measures precedence. Overcrowding is said to be "Granger-caused" by jail capacity if jail capacity helps explain the prediction of institutional overcrowding. This task involves constructing a pooled time series database consisting of the rated capacity for the five adult jail facilities in Orange County and the corresponding average daily jail population above the rated capacity.

This research will assist in improving the local administration of justice by providing a scientific basis for evaluating merits of recent policy actions aimed at remedying institutional overcrowding in Orange County jails. In November, 1996, the County's Board of Supervisors approved an Environmental Impact Report recommending the expansion of the 713-bed James A. Musick Branch Jail to accommodate as many as 7,584 inmates. Proponents of the jail expansion have stressed the urgent need for more jail capacity to address overcrowding in the County's adult detention facilities.

This expansion would convert a minimum-security facility into one of California's largest maximum-security jails, requiring a substantial financial commitment from the public for the jail's construction and daily operation. County residents who live near the Musick facility have expressed fear that a maximum security jail would put them and their children at risk and depress property values. Unfortunately, public discourse over the jail expansion has not addressed a more fundamental issue: Does jail capacity *reduce* institutional overcrowding? Seemingly, more jail capacity should counter jail overcrowding, however to date there is no evidence documenting this supposition. This research will address this negligence. The results of this project will contribute to the concerns of present-day criminal justice policies by providing evidence on the impact jail capacity has on institutional overcrowding in Orange County jails.

Urbanization Economics: The Location of Private Firms in California Counties

Abstract

Since the publication of Aschauer's (1988) seminal paper on the productivity of public expenditures, economists have increasingly focused attention on the links between public capital and private economic activity. Aschauer's work concluded that the slowdown in U.S. productivity growth could be explained in large part by declining investments in public capital. Recent attention given to the serious decay of the nation's highway and road stock has raised questions of whether these assets significantly impact private economic activity.

Recent works on transportation infrastructure have considered how highway capital stock impacts the location choices of private firms. Boarnet (1995) showed that highway capital inputs in California counties positively effected private economic activity in those counties with greater capital stock but at the expense of other neighboring counties with less transportation capital stock. In other words, transportation infrastructure works to shift economic activity from one location to another rather than increasing aggregate economic activity (Boarnet, 1995).

This study examines the impact highway capital stock and agglomeration economies have on the location of private business concerns in California's 55 counties. My approach differs from previous works on the subject in that I do not consider public highway and street capital as an unpaid input factor of production. Instead, I develop a model that uses urbanization economies and highway capital stock to explain the variation in the location of manufacturing, services, construction, and other such firms in 58 California counties between 1970 and 1996. This research potentially has important implications for regional economic development; if highways facilitate the movement of firms in accordance with agglomeration economies, local governments that wish to build transport infrastructure based on perceived economic gains may want to first consider the influence urbanization economies within and outside of the immediate project area.

Let's Do Launch: Comparative Advantage in Rocket Launchers

Abstract

Ballistic missiles share many overlapping technologies with SLVs. The Soviet *R-7* SLV that lifted *Sputnik* and Yuri Gargarin into orbit, doubled as an intercontinental ballistic missile (ICBM) during the 1960s. Modifications to the *Atlas* ICBM made possible John Glenn's Earth orbit in 1962. Although the *R-7* and *Atlas* ICBMs were retired more than 35 years ago, they remain in production today as key SLVs for Russia and the United States. China's SLVs, the *CZ-1*, *CZ-2*, *CZ-3*, and *CZ-4*, are based on the *DF-4* or *DF-5* ICBM. From a cost perspective, a SLV derived from a ballistic missile capitalizes on existing hardware, tooling, technology, and workforce.

Ostensibly, commerce in satellites and rockets has been limited by concerns around technology transfers. However, following the 1986 Space Shuttle *Challenger* accident, the United States allowed the China Great Wall Industry Corporation to bid on launching services in an effort to relieve the backlog created by a moratorium on civilian use of the Shuttle. The possibility of indirect technological transfers to China's ICBMs via the *CZ* rockets were presumed and considered consistent with our continuing Cold War rivalry with the Soviet Union. Following the collapse of the USSR in 1991-92, the U.S. allocated launching quotas to Russia.

Chinese and Russian aerospace exports increases rapidly over this period. China's total aerospace exports increased to $300 million in 1990 up from $20 million in 1985. Similarly, the value of Russian rocket contracts with firms in the West went from zero in 1991 to approximately $1.5 billion in 1998. Meanwhile, the U.S. share of the free world's commercial launches fell to 25% in 1994 from 100% in 1984. This dramatic decline in the U.S. position triggered an unprecedented debate on launcher cost competitiveness as well as protectionist legislation disguised in national security rhetoric

Marginal costs are an important component of total launching cost and are widely regarded as being crucial to international competitiveness. I am currently building an empirical model that explains marginal costs with a generalized Cobb-Douglas cost function augmented by country-specific intercepts. Significant intercept differences would be evidence of a comparative advantage (i.e. differences in factor endowments: labor and capital). Such a finding would have important policy implications regarding satellite commerce. Introduced by David Ricardo in 1817, the theory of comparative advantage contends that two nations can grow richer by specializing and exporting the commodity of its comparative advantage.

Causality Between the Strategic Missile Arsenals of the U.S. and USSR/Russia

Abstract
There is controversy in the international relations literature on the causes of the superpower arms race. The external influences perspective attributes the arms race to 'action-reaction' phenomenon. This theory argues that the United States and Soviet Union mutually influenced one another's strategic plans. Alternatively, the internal influence school attributes arms races to bureaucratic politics, inter-service competition and the military-industrial interests. My research involves applying the Granger test for causality to the strategic missile arsenals of the superpowers and the missile arsenals of their respective military services to test the validity of these two theories. The Granger test does not test for causality *per se*, but precedence.

My results show U.S. ICBM deployment *Granger caused* Russia's ICBM arsenal however the USSR. ICBM deployment did not *Granger cause* the deployment of America ICBMs. Moreover, the interaction between Air Force and Navy missiles resembled the action-reaction dynamic. The USSR land-based ICBMs *Granger caused* the Soviet Navy's ballistic missiles but not the reverse. I have submitted a complete manuscript further detailing these results to the *Journal of Conflict Resolution*. The journal's editor indicated that my article would be reconsidered if the referee comments were addressed.

ABSTRACT OF THE DISSERTATION

Ballistic Missile Proliferation: A Self-Organizing Phenomenon

By

Daniel T. Barkley

Doctor of Philosophy in Economics

University of California, Irvine, 2000

Professor Art De Vany Chair

Ballistic missile proliferation has emerged as important topic in international relations. Once confined to a select group of industrialized nations, ballistic missiles have spread throughout many parts of the world. Proliferation of this particular weapons platform is salient because of its potential to deliver weapons of mass destruction to densely populated areas. Contemporary analysis of ballistic missile proliferation tends to explain missile proliferation as the latest bad habit of the so-called rogue-states. My methodological approach is unique in that I examine the phenomenon as a dynamic process of a complex system in which individual choices are rational and intended to achieve national security goals. Collectively, however, these choices have unintended macro-level effects. Such a process is not unfamiliar to economics. Indeed, the invisible hand theorem is more than a proposition about the computation of a price vector but a statement about the inherent order in human affairs, an order that is the "result of human action but not human design" (Adam Ferguson, 1767).

Traditionally nations have countered defensive weapons with offensive weapons: castle were countered by cannons; forts were counter by tanks; ships were counter by missiles, jet aircraft were counter by radar and air defenses and so on. Ballistic missiles

changed this defense-offense sequence of weapons innovation. Unlike these earlier weapons systems, which can be neutralized before or after being mobilized, defense against ballistic missiles is extremely difficult. When faced with ballistic missile threats, nations often acquire ballistic missiles themselves as a deterrent.

A ballistic missile threatens not only its intended target but menaces all agents within its range. Consequently, missile procurement by one state can precipitate missile procurement from the various nations within the striking distance of the newly acquired missile. Using a panel data set of 119 countries from 1967 to 1997, I show that missile threats can explain over 80% of the variation in missile ranges. I also model the decision to arm with a discrete choice model that explains the probability of procuring ballistic missiles as a function of the number of foreign missiles capable of striking a country. I find that the probability a country procures missiles increases nonlinearly as the number of neighbors with missile increases. Moreover, missile proliferation exhibits threshold dynamics: countries are likely to get ballistic missiles when they have at least two neighbors with ballistic missiles.

I simulate ballistic missile proliferation as a cellular automation, that is a lattice in which the site strategy (arm or disarm) is determined the number of neighboring sites with missiles capable of striking the cell. The decision rules, which arm or disarm sites are based on my discrete choice model. Starting with a random distribution of armed sites and unarmed sites, the lattice system *self-organizes* into clusters of armed and unarmed sites. These simulation configurations resemble the real world patterns of ballistic missile proliferation.

CHAPTER 1

Ballistic Missile Proliferation: An Introduction

When the first ballistic missiles were deployed in the 1940s and 1950s, they were viewed as long-range battlefield support or a means to deliver artillery deep into enemy territory. Battlefield missiles were also intended to discourage enemy troops from amassing large concentrations needed for controlling and holding territories.[1] As distinct from strategic targets, tactical targets are typically many in number, tend to be point rather than area targets and may be mobile or heavily defended. A successful tactical strike therefore requires many sorties, large payloads, and high accuracy (Harvey, 1992, p. 70). Early ballistic missiles such as the German *V-2* (1942-45) could only carry a conventional payload of 750 kg and lacked the accuracy and reliability to be an effective tactical weapon. At this time, manned bombers like the American *B 70* or the British *Lancaster* offered far more range, mobility, and concentrated firepower than ballistic missiles (Karp, 1996, p. 37).

However, as technology advanced the range, payload, reliability, and accuracy of ballistic missiles, it became apparent that the technical characteristics of these weapons would fundamentally alter the way countries strategize about warfare. In particular, it was realized that the missile's supersonic speed gave the elements of surprise and

---

[1] General Dwight Eisenhower (1952, p. 294) noted in the *Crusade in Europe*, had the *V-2* been available six months earlier, the landing a Normandy would have been impossible. The tactical advantages of ballistic missiles have not been ignored. The Soviet Union provided Afghanistan with hundreds of *Scud B* missiles in 1979 in hopes that the missiles would prevent the rebels from taking key cities and towns. Similarly, The Congo purchased both 180 mile *Scud B* and 300 mile *Scud C* missiles from Iran in November, 1999 to presumably discourage rebel forces from taking control of Congolese cities and territories. The Congo is the size of Western Europe and like Afghanistan it is virtually without roads to the hinterland. Ballistic missiles provide the Congo an inexpensive offensive capability that does not require runways, refueling, trained pilots or expensive spare parts. Fired from its borders with Uganda or Rwanda, the *Scuds* could easily strike Kampala, Uganda or Kigali, Rwanda.

preemption new meaning. With the advent of intercontinental ballistic missiles (ICBMs) continental distances could be reached in 30 minuets, whereas it took the fastest jet eleven hours to travel as far. Deployed on submarines in the mid-ocean, submarine launched ballistic missiles (SLBMs) might strike in even less time (Arms Control Association, 1989).

While ballistic missiles offer nations a powerful offensive weapon, they concomitantly complicate defense. Unlike other offensive weapons, defense against ballistic missiles is extremely difficult. Combat aircraft for instance, are relatively slow and vulnerable on the ground, in flight and are likely to be detected long before approaching their target. In contrast, road or rail mobility, hardened silos or the vast oceans of world can protect ballistic missiles from first strikes. Even if they are detected in flight, supersonic speeds make ballistic missiles virtually invulnerable to air defenses. Table 1.1 compares the Mach number, range, and payload for selected U.S. military flight vehicles. What ballistic missile lack in payload capability, the make-up in speed.

Table 1.1

Mach No., Range, and Payload for Selected U.S. Ballistic Missiles and Aircraft.

Flight Vehicle	Mach Number	Range (nautical miles)	Payload (pounds)
Honest John	2.4	21	1625
Lance	3.0	75	400
Jupiter (IRBM)	15.1	1,200	2,200
Pershing II (IRBM)	8.0	1,200	650
Polaris A3 (SLBM)	10	2,500	1,500
Tident II (SLBM)	17	7,500	3,000
Atlas (ICBM)	22	9,000	3,000
Minuteman III (ICBM)	19.7	6,300	950
F/A 18 A-D (Fighter)	1.8	550	17,000
F-117 (Stealth Fighter)	1.5	550	14,000
B-1B (Bomber)	1.2	7,500	125,000
B-2B (Stealth Bomber)	0.9	7,300	50,000

Notes. Sources: *U.S. Missile Data Book*, 1996, and the *U.S. Military Aircraft Data Book*, 1997 Data Search Associates; Mach number refers to velocity at burnout (i.e. when the engines cut off) for missiles and the maximum speed for aircraft. Mach 1 is approximately 750 miles per hour (mph), therefore the *Polaris A3*'s velocity at burnout is approximated at 7,500 mph. SRBM = short range ballistic missiles; IRBM = intermediate range ballistic missiles; SLBM = submarine launched ballistic missiles; ICBM = intercontinental ballistic missiles.

During the Cold War era, the United States and Soviet Union deployed a large number of nuclear ballistic missiles. Attempts at ballistic missile defense, sometimes called antiballistic missiles or ABMs proved to be ineffective beyond the protection of a single missile site.[2] Without a reliable defense against ballistic missiles the United States and the Soviet Union came to rely on thousands of nuclear ICBMs and SLBMs for mutual assured deterrence or MAD. MAD rested on mutual threats: each side threatened that if it were attacked, it would respond with a nuclear strike against the other side. However, because of the enormous destructive capacity of nuclear weapons, both sides would suffer devastating destruction in an all out nuclear exchange. Thus, both sides were mutually deterred from initiating hostilities. This 'strategic equilibrium' between opposing offensive forces was called the 'balance of terror' and was a distinct departure from the offense-defense weapons strategy that had dominated in international warfare since the Roman conquests (Quester, 1977).

During the Cold War, ballistic missile proliferation beyond the two superpowers was presumed to be a manifestation of a bipolar world and therefore inevitable. For the United States and Soviet Union short and intermediate range ballistic missiles were considered to be tactical or battlefield weapons, and as such were supplied to their

---

[2] American efforts to develop a anti-ballistic missile system have been frustrated by of exorbitant cost and limits of available technology (Thee, 1986, pp. 7-8). Recent testing of missile defenses has produced four success out of 18 tries (Briefing Book on Ballistic Missile Defense, 1999). The most advanced system now under development is the U.S. is the army's Theatre High-Altitude Area Defense system (THAAD). In four test against specially designed targets with known trajectories and characteristics that fell well within the expected performance range of the system, the THAAD interceptor failed in all four attempts ("Rush to Failure" *Bulletin of the Atomic Scientist*, Joseph Cirincione, 1998). General Lester Lyles, the current director of the Ballistic Missile Defense Organization, the government agency responsible for development of ballistic missile defense compared striking a missile equivalent to "hitting a bullet with a bullet in space". According to Gen. Sheldon, Chairman of the Joint Chiefs of Staff, "... we do not yet have the technology to field a national missile defense. We have put some $40 billion into the program over the past 10 years. But today we do not technologically have a bullet that can hit a bullet." *Sea Power Magazine*, February, 1999.

respective client states throughout the world.[3] The East-West conflict overshadowed international concerns regarding the threat ballistic missile proliferation might pose to regional stability. NATO allies (1957-1983) as well as Australia (1970), South Korea (1961), Israel (1972) and Japan (1969) received ballistic missiles and/ or relevant technology from the United States.[4] The United States supplied *Thor, Pershing*, and *Jupiter* IRBMs as well as shorter ranged *Honest John, Lance, Corporal,* and *Sergeant* missiles to NATO allies.[5] These missiles could deliver either nuclear, chemical, or conventional warheads up to ranges of 1,500 miles.

Around the same time, the Soviet Union began providing its client states with comparable ballistic missile technology. In 1957, the Soviet Union armed China with the 600 km *SS-2* ballistic missile.[6] In that same year, the Soviet Union shipped *FROG 4* and *FROG 5* rockets to North Korea, Egypt, and Algeria (Nolan and Wheelon, 1990). The following year, Moscow secretly placed two *SS-3s* launchers in Vogelsang, southeast of Berlin.[7] Starting in the late 1960s, Warsaw Treaty Organization (WTO) members began procuring *FROG, SS-12, SS-21, SS-23,* and *Scud B* missiles from the Soviet Union.[8]

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[3] The Strategic Arms Limitation Talks (SALT I, II) agreement of 1972 and 1979 pertained to ICBMs and SLBM and not tactical missiles.

[4] On sales of U.S. space launchers to Australia and Japan, see Smith, M.S. and Sheldon II, C.S., *Space Launch Activities of the United States, Soviet Union and other launching Countries/ Organizations: 1957-1983*, Report 83-124 SPR (Congressional Research Service: Washington, D.C. March 15, 1983).

[5] US *Thor* IRBMs, which were controlled by British-American dual key arrangement, had been installed at Feltwell, North Luffenham, and Hemswell were operational in 1958. "Russian nuclear rockets aimed at Norfolk in 1958", *The Times* (London), January 18, 2000. In August 1959, the U.S. Air Forces in Europe Two fifteen-missile *Jupiter* squadrons were deployed to Italy in April, 1960. In early November, 1961, a 15 *Jupiter* missiles deployed to Cigil Airfield near Izmair, Turkey became operational (Neufeld, 1990, pp. 225-226).

[6] Chinese engineers mastered reverse engineering the *SS-2* and built their first generation of ballistic missiles by gradually improving the *SS-2's* engines and adding on rocket stages (Karp, 1996).

[7] The missiles had a range of 750 miles threatened London and Paris.

[8] At its height, the Soviet Union Union's tactical nuclear arsenal included eight different types of missiles and an estimated 6700 warheads (Cochran, Arkin, and Norris, 1989, p. 190).

As short and intermediate range ballistic missiles spread through out various parts of the world, it became apparent they had important military applications beyond the battlefield or the Cold War. In particular, their range placed major cities within striking distance. Cities are particularly vulnerable to ballistic missile attack. Population centers are considered soft targets against which high accuracy is not crucial and where, unlike tactical military targets, the timing of the attack is not crucial. Cities are also large, immobile, and therefore difficult to defend.

The threat ballistic missiles pose to population centers is not new. During the later years of World War II, Germany launched thousands of *V-2* missiles at European cities causing thousands of civilian casualties.[9]

Ballistic missiles are with few exceptions relatively inaccurate. Inaccurate missiles are suitable for large, fixed objects like cities rather than troop concentrations. Many developing nations offer a potential aggressor a small set of lucrative targets. Because of their sharp population asymmetries among city sizes, many developing countries are considered to be 'one-bomb' states; places where a strategic attacks on a major population center could cause panic disrupt the national economy as well as military production (MacCain, 1989; Harvey, 1992). In fact, the ballistic missile's "greatest effect is not in war as military instruments but as political instruments in time of peace" (Karp, 1996). But political strategy does not preclude ballistic missiles from war time usage. Both combatants of the Iraq-Iran War (1980-88) launched hundreds of ballistic missiles at one another's cities in the so-called the 'War of the Cities' campaign

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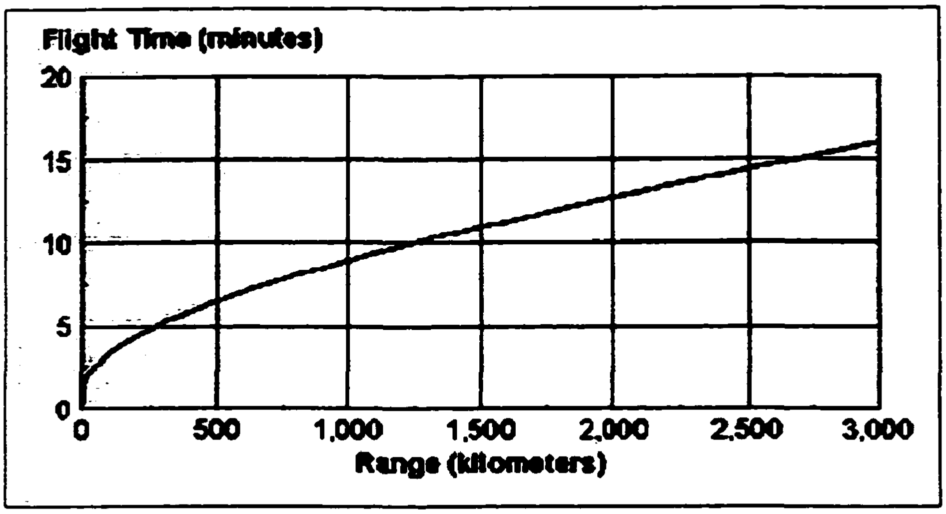
[9] The *V-2* rocket was the first supersonic guided missile. The 13-ton rocket struck its targets as speeds of 2,386 mph thus arriving without warning. Between September 1944 and March 1945, 518 rocket hit London causing 9,000 causalities; Antwerp, its other major target received 1,341 missiles and suffered 30,000 casualties *(The Atlas World of Warfare: Military Innovations That Changed History)*.

during the final months of that war. Among those fired by Iraq were 160 *Al Hussein* missiles at Tehran. These missiles caused 2,000 Iranian casualties, the evacuation of Tehran and a sever disruption of Iran's war economy. Several analysts attribute the *Al Husayn* attacks on Tehran as critical in getting Iran to negotiate an end to the protracted war (Karsh, 1989; Navis, 1993). Despite heavy losses, Iraq emerged as the 'winner', due in large measure to its use of ballistic missiles against Iranian cities.

A ballistic missile with a range of 600 km has a flight time of about seven minutes; whereas a strike aircraft would take a half an hour at normal cruise speed, to cover the same distance (Harvey, 1992, p. 62). The Iraqi *Al Husayn*'s fired at Israel during the Gulf War took less than ten minuets to reach Tel Aviv. Figure 1.1 shows a range (in km) versus flight time (in minutes) graph, for ballistic missiles. Table 1.2 shows distances between selected world cities.

Figure 1.1 Range vs. Flight time for Ballistic Missiles



Source: Trost, 1997

Table 1.2

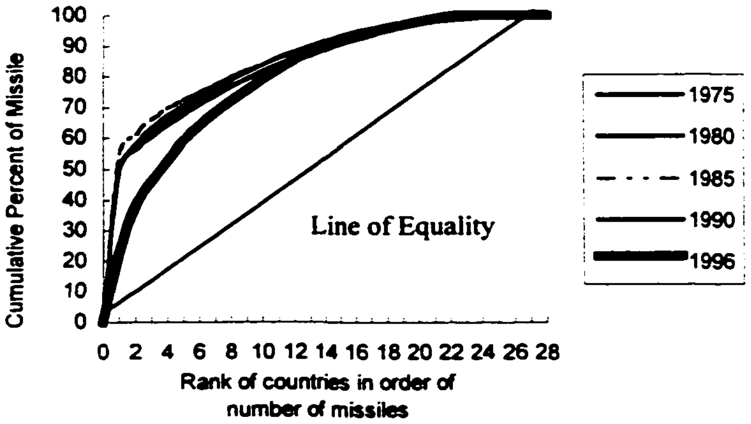
The Distance Between Selected Cities

City, Country	City, Country	Distance (km)
Damascus, Syria (*Scud B*)	Tel Aviv, Israel (*Jericho II*)	213
New Delhi, India (*Agni II*)	Lahore, Pakistan (*Ghauri II*)	443
Shanghai, China (*M-9, M-11*)	Taipei, Taiwan	687
Bonn, Germany (*Pershing II*)	Warsaw, Poland (*Scud B*)	989
Baghdad, Iraq (*Al Husayn*)	Tehran, Iran (*Shahab 3*)	712
Cairo, Egypt (*Scud C*)	Tel Aviv, Israel (*Jericho II*)	410
Amman, Jordan	Jerusalem, Israel (*Jericho II*)	71
Kabul, Afghanistan (*Scud B*)	Islamabad, Pakistan (*Ghauri II*)	374
Tehran, Iran (*Shahab 3*)	Riyadh, Saudi Arabia (*CSS 2*)	1,325
Kuwait City, Kuwait (*FROG*)	Baghdad, Iraq (*Al Husayn*)	523

Notes. Ballistic missiles travel several times the speed of sound (750 mph), which means their flight time is measured in minuets. Figure 1.1 shows a range (in km) versus flight time (in minutes) graph, for ballistic missiles. Table 1.2 shows distances between selected world cities. Short flight time minimizes the chances of a target moving before it is struck as well as the warning time for the would be defender. High speeds also decrease the chances of effective active or passive defensive measures by the target (Trost, 1997). Missile are in parenthesis.

Despite the excited headlines about ballistic missile proliferation, the number of armed states and the distribution of ballistic missiles remained relatively constant over time. Figure 1.2 shows the Lorenz Curves for the 1975, 1980, 1985, 1990, and 1996 for short and medium ranged surface-to-surface missiles. Data for this particular category of missiles is published annually in the International Institute for Strategic Studies' *The Military Balance*.

Figure 1.2 Lorenz Curves Comparing the International Distribution of Short and Intermediate Ranged Ballistic Missiles.



If every country had exactly the same number of surface-to-surface missiles (SSMs), the cumulative curve would be a straight line. The visual effect of concentration or dispersion is shown as the area contained between the Lorenz Curve and the Line of Equality. It is immediately apparent from Figure 1.2 that a few countries accounted for a high percent of missiles. More specifically, the USSR accounted for over 50% of the SSMs from 1975-1990.

The collapse of the USSR in 1991-1992 and the establishment of new nations from the former Soviet Union, fundamentally shifted the worldwide distribution of ballistic missiles by 1996. The huge Soviet arsenal, which numbered more than 1,500 *Scud*, *FROG*, *SS-21* and *SS-23* missiles, was unevenly divided among Belarus, Khazastan, Russia, and the Ukraine. At end of the Cold War, the Warsaw Treaty Organization (WTO) was dismantled and ballistic missiles were eventually withdrawn from East Germany, Hungary, and Poland while the missile arsenals of the Czech Republic and Yugoslavia were eventually divided between Slovakia and Bosnia-Herzegovina respectively.

Although the total *number* of armed countries has not changed dramatically, the particular countries with ballistic missiles has changed over time. Table 1.3 ranks the *top ten* nations in terms of the estimated number of short and medium missile deployed in 1975 and 1996.

TABLE 1.3

Rank of Countries in Terms of Size of Ballistic Missile Arsenal

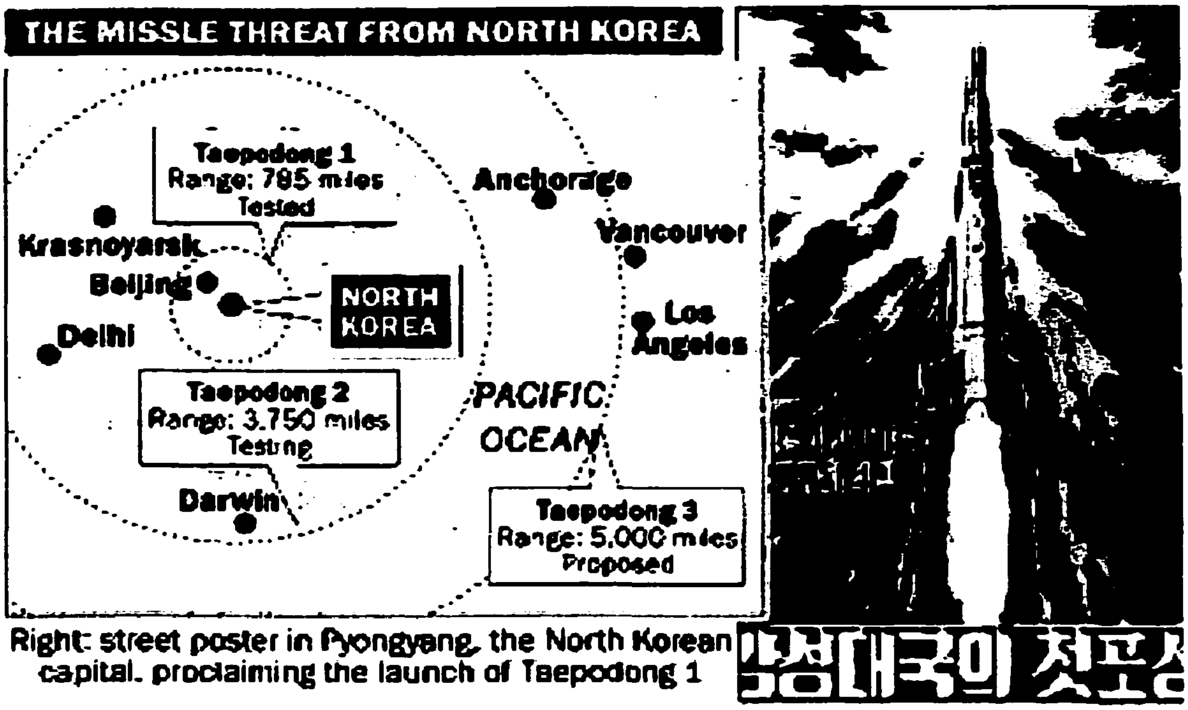
1975 Rank	***Estimated Number of Missiles***	1996 Rank	***Estimated Number of Missiles***
1. USSR*	1000	1. Iran*	410
2. West Germany	162	2. Ukraine	276
3. USA*	109	3. Russia*	144
4. Poland	79	4. Israel*	120
5. Czechoslovakia	67	5. Libya	120
6. Syria	66	6. North Korea*	84
7. Bulgaria	50	7. Belarus	78
8. China*	50	8. Czech Republic	66
9. Israel*	50	9. Bulgaria	64
10. Romania	48	10. Syria*	64

Notes. The Military Balance; Navias, 1993; Nolan, 1991; Karp, 1996. * Donate domestic missile producer.

In 1975, the only MENA countries in the top ten were Israel and Syria, by 1996 the MENA number doubled, with Iran occupying the top spot. Three of the five largest ballistic missiles arsenals in 1996 were in the MENA. Also the absolute size of the ballistic missile arsenals have become larger over time. With the exception of the Soviet Union, the ten top countries in 1996 had larger arsenals than did the top ten countries in 1975. Among the ten largest ballistic missile arsenals in 1996, Israel's was the only one without *Scud* missiles. North Korea, South Korea, Egypt, Taiwan, India, Pakistan, and Iran have fielded domestically produced ballistic missiles. Argentina, Brazil, India, and Pakistan have used their space programs as a precursor to ballistic missiles development.

As missile ranges continue to increase, more countries become vulnerable to ballistic missiles, more nations are likely to acquire missiles as a consequence of that vulnerability. While only Russia, China, France and Great Britain have ballistic missiles that can target the United States, there is a growing concern about the safety of Western military installations and forces overseas.

On August 31, 1998, North Korea sent shock waves throughout North Asia by test-firing the *Taepodong 2* ballistic missile. The three-stage soared over Japan and traveled almost 4,000 miles before crashing into the ocean near Alaska. The proposed *Taepodong 3* is more powerful and could reach all of the Indian sub-continent, Persian Gulf countries, Taiwan, Australia, and much of Alaska. Figure 1.3 shows the ranges and threatened cities for the *Taepodong* family of ballistic missiles.



Right: street poster in Pyongyang, the North Korean capital, proclaiming the launch of Taepodong 1

Source: Sandia Laboratories

Figure 1.3 *Taepodong* Missiles and Ranges. The *Taepodong* tests surprised and angered its neighbors, initially believed to be a ballistic missile test. Although the solid-fueled third stage of the rocket failed and the small satellite payload was destroyed, the rocket flew in an arc over Japan, raising fears in Tokyo of unexpected military vulnerability. Pyongyang announced the T*aepodong* satellite launch with a great fanfare (see street poster to in Figure 5), timed to coincide with the 50th anniversary of the foundation of their state, but every indication is that the satellite fell into the sea. *The Korea Herald* (Seoul), September 16, 1998; *Electronic Telegraph* (London), September 17, 1998.

Concerns about the proliferation of ballistic missile technology led the United States and six other industrialized nations to form the Missile Technology Control Regime (MTCR) in 1987. The MTCR is an informal international agreement that prohibits the transfer of ballistic missiles and related technologies to non-member states. By 1997, the regime's membership tripled to 21 partners. Over the course of the regime's history, the MTCR guidelines and Annex became the international standard for missile related technology export policy.[10]

While the Regime is credited with terminating missile programs in Argentina, Brazil, and South Africa, it has limited impact in Asia and Middle East. In fact, ballistic missile ranges and payloads in existing arsenals have significantly increased between 1987 and 1997. Figure 1.4 compares the average range and average payload for ballistic missile in the Middle East and North Africa (MENA), Asia, Europe, and the World in 1987 and 1997. Ballistic missile ranges have increase in every region except, Europe where ranges fell slightly.[11]

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[10] The MTCR is a multilateral regime that restricts the transfer of ballistic missile technology to non-member states. Originally, the regime's restrictions applied to ballistic missiles capable of lifting 500 kg to a distance of 300 km. In 1991, the payload restriction was lowered so that in effect the regime now covers surface-to-surface missiles with a range over 150 km. Moreover, the regime prohibits transfers of space launcher technology to any country working on ballistic missile development (Karp, 1996, p. 27).

[11] In Chapter 5, I explain the a variation in missile range and payload with a variable *Norms*, the ratio of sum of the GNPs of countries observing MTCR regulations over the sum of the GNP of all countries in the sample. While the MTCR coefficient explaining the variation in defection is negative the corresponding MTCR coefficient explaining the variation in missile payload is insignificant. MTCR is a regime regulating the international trade of missile technology; it does not directly regulate indigenous ballistic missile innovations. Consequently, international norms arising from the regime should only impact the transfer of missile technology among states. This result is of interest because it indicates the limits of arms control on ballistic missile innovations.

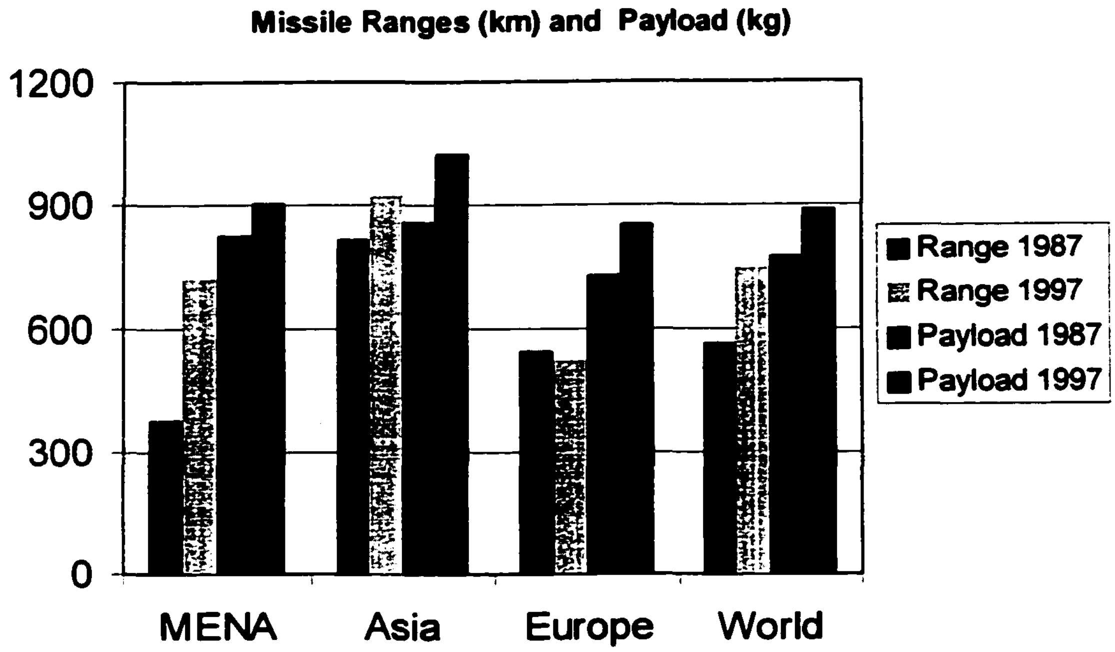

Figure 1.4 Average Ballistic Missile Range and Payload in the Middle East – North Africa (MENA), Asia, Europe and the World. These averages are for the longest range ballistic missiles and heaviest payloads.

Ballistic Missiles: Definition and Scope

Aaron Karp (1989) defines a ballistic missile to be "any unmanned, self-propelled weapons delivery vehicle that can be used in a surface-to-surface role in and which sustains a ballistic trajectory [approximated by a parabola] through most of its flight without relying on aerodynamic lift." Aerodynamic lift forces on flight vehicles are usually generated from wings, consequently ballistic missiles have no wings as do airplanes and cruise missiles. A missile's flight trajectory is sustained by the momentum generated from the rapid release of hot gases the vehicle's engine exhaust nozzle.[12] Ballistic missiles are sometimes called 'surface-to-surface' missiles or SSMs because of

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[12] Rocket propulsion is achieved by applying a force called thrust to a vehicle. Rocket propulsion depends on Newton's third law of motion: "action is equal and opposite to reaction." If matter is ejected from a free

their trajectory.[13] This research is primarily concerned with the proliferation of short and intermediate range ballistic missiles. These missiles have ranges between 30 and 3,000 kilometers (km) and are capable of delivering conventional and non-conventional warheads to desired targets. There is considerable variation among missiles in this range category (See Appendix). Some of the shorter ranged missiles such as the *Honest John* and *FROG* ('Free Rocket Over Ground') are unguided. Missiles like *Scud-B* use liquid fuel, where as the Chinese *M-11* uses solid fuel. Longer ranged intercontinental ballistic missiles (ICBMs) and submarine launched ballistic missiles (SLBM) are not directly addressed here.[14]

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body with a certain momentum in a certain direction, then the body gains equal momentum in the opposite direction.

[13] The 'surface-to-surface' designation is somewhat misleading. Silo based ballistic missiles such as the *Minuteman III* are launched from below the earth's surface. Ballistic missiles such as the *Trident II* are carried on nuclear submarines and are launched from below the ocean's surface.

[14] Until Beijing deployed its *DF-5* ICBM in 1979, ICBM technology had been confined to the United States and the former Soviet Union. The *Atlas*, America's firms ICBM was operational in 1959, the Soviet Union tested the first world's first ICBM *SS-6* / *R-7* in 1957. France is currently developing a ballistic missile, the *M-25* that will have intercontinental ranges.

Game Theory and Missile Proliferation

Considerable scholarship has been made in applying the gaming models to arms racing. As a theory of rational decision making, arms racing gaming models specify how players (or countries) should act to achieve their national security goals. Chapter 2 applies game-theoretic models of deterrence (e.g. Chicken), Prisoners' Dilemma, and SSM- an original game, to ballistic missile proliferation in South Asia and the Middle East. Each of these two-player models highlights a key aspect of contemporary ballistic missile proliferation.

While the game-theoretic models help explain the behavior of a two-player arms race, they do not address the impact strategic choices might have on other neighboring states.[15] Ballistic missiles, like most weapons, are not country specific. Missiles can threaten several multiple countries. Consequently, missile proliferation is a *n*-person-repeated game. Peter Albin (1998) modeled a *n*-person repeated prisoners' dilemma with a cellular automata. His model explains the problem faced by fully rational players who seek to improve expected gains above that associated with universal defection. Chapter 3 replicates Albin's experiments using the payoff structures from the games discussed in Chapter 2. Chapter 3's simulation experiments show that cooperation can emerge in multi-player games in which universal defection is the dominant strategy. That is, multiple players are capable of sustaining a "Nash-like" equilibrium without formal or external agreements that bind states to promises not to pursue their dominant strategies.

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[15] Jervis (1978, p. 181) notes that " ... arms sought to only secure the status quo-may alarm others and others may arm, not because they are contemplating aggression, but because they fear attack from the first

Ballistic Missiles Proliferation: A Systems Approach

Social science is built on the understanding of systems and that systemic effects arise from the unintended consequences of complex interactions. Unfortunately, the basic concept of a system is ignored the analysis of missile proliferation. The contemporary weapons proliferation literature often examines ballistic missile proliferation on a country-by-country basis (Nolan, 1991; Navias, 1993; Potter and Jenks, 1994; Karp, 1989; Karp, 1996; U.S. Senate Committee on Government Affairs, 1998). While case studies can be very informative, they cannot be aggregated or generalized in order to ascertain the stability of the international system vis-à-vis ballistic missile proliferation.

Seeking to understand how ballistic missile proliferation effects the international system by looking at countries separately seems inappropriate for several reasons. First of all, missile threats are multilateral rather than bilateral. A ballistic missile not only threatens an intended adversary but all nations within its range. Unintended missile threats can trigger missile procurement from the various nations within the striking distance of the newly acquired missile.

A systemic approach emphasizes how several preferences for national security stem from a country's position in the international system. As Jervis stressed: "the systems approach is the belief that structures matter and that the internal characteristics of the elements matter less than their place in the system" (Jervis, 1997, p. 11). This is why very different kinds of countries (e.g. democracies, dictators, theocracies, etc) have ballistic missiles.

The difference between the parts and the system is often expressed as the emergent properties of the latter (De Vany, 1996). Emergence means that identifiable

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state." Thus, in trying to increase one's own security one can actually decrease it.

structures or patterns emerge from systems without intent. This order is not reducible from the actions of one or a few system members but arises from interaction among all system members. The notion that systems in which randomness and chaos seem to spontaneously emerge into an unexpected order is not new to economics. A familiar example of the emergent property of self-organizations was stated more than two centuries ago when Adam Smith wrote the way that markets lead participants, " as if by an invisible hand," to outcomes no one intended. Individually, each person is primarily concerned with their maximizing his or her own consumer or producer surplus, concepts they are generally unaware of (Krugman, 1995, p. 3).

Chapter 4 explores the emergence of spatial ordering in ballistic missile proliferation. Internationally, there appears to be a tendency among nations with and without ballistic missiles to be geographically contiguous. For instance, Libya, Egypt, Israel, Syria, Saudi Arabia, Iran, and Yemen-share at least one common border and all have ballistic missiles. Algeria, Tunisia, Morocco, and Mauritania also share at least one common border but do not have ballistic missiles. *Spatial autocorrelation* is said to exists when the value of a variable at a given location depends on the value of the variable at contiguous locations. Spatial autocorrelation means neighbors have influences on each other in geographic space. In Chapter 4, I explore the emergence of spatial autocorrelation in ballistic missile proliferation using a classification called the *join count statistic*. If two countries share a common boundary they are said to be linked by a join. The join count is a classification of international borders in to one of three mutually exclusive categories: a join can either connect two cooperating (CC) counties countries, two defecting (DD) countries or a D to a C (DC) country. These borders are designed CC *joins*, DD *joins*, and DC *joins* respectively.[16]

Intuitively, it is understood that the joins act as an indicator of the presence and type of spatial autocorrelation. As ballistic missiles spread over time and across regions, the number join count in each category changes. The critical step in the logic is to view the changes in the number of joins as the result of a ballistic missile proliferation. For instances, as the number of CC or BB *joins* increases, a corresponding decrease in DC results. When this happens, similar types of countries (e.g. armed or unarmed) are clustering together. If, however, the number of CC, DD, and DC are close to the expected values (under the null hypothesis of no spatial autocorrelation), then ballistic missiles are randomly distributed in space. Starting with the equivalent of a random distribution of join counts in 1967, Chapter 4 shows a highly regular pattern of spatial autocorrelation emerges in 1990.[17]

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[16] The DC category included the CD cases.
values do not mean that we must accept the null hypothesis of a random distribution, but we have

Discrete Choice and Missile Proliferation

Discrete choice models provide a way of looking at a richer set of hypotheses concerning missile proliferation not possible with the game theory or the join count analysis. Discrete choice is an attractive approach it allow us to examine ballistic missile proliferation along with factors such as country size, shape, spatial statistics as well as institutional factors such as norms. Most importantly, we can use the discrete choice framework to model the threshold dynamics that trigger local proliferation. Understanding the micro-level dynamics driving ballistic missile proliferation is an essential first step in understanding ballistic missile proliferation as a self-organizing system.

Economics, as a discipline concerned with choice, has much to offer in the theoretical development of arms racing models and missile proliferation. A country's decision to arm with ballistic missiles is a discrete choice. The general class of regression-based models for which the out come or dependent variable takes discrete binary values, is known as qualitative response (QR) models (Greene, 1993, p. 635) or discrete choice models. In these models, the dependent variable is discrete outcome, such as defecting or cooperating.

Chapter 5 uses regression analysis to explain the decision to defect with the number of defecting neighbors holding constant country size, the number of borders, and institutional factors. My panel data set includes 119 countries from 1967 to 1992 and 139 countries from 1992-1997. This period was selected because it coincides with the time frame in which ballistic missiles began spreading beyond Europe (see Table A2 in Appendix). These years also include the implementation of international export controls on the transfer of ballistic missile technology (1987-1997). Starting in 1967, this panel

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insufficient evidence to reject the null.

avoids complications associated with the colonial era. Finally, the time periods allows us to examine missile proliferation before and after the Cold War.

I find that the probability a country arms increases nonlinearly as the number of armed neighbors increase. Moreover, missile proliferation exhibits threshold dynamics: countries are more likely to arm when they have at least two armed neighbors.

A state's response to armed neighbors need not be constrained to the binary choice: cooperate or defect. Countries can change the range and payload of their ballistic missiles in response to missile threats. Chapter 5 also explains up to 82% of the variation missile range and payload for the panel data set using ordinarily least squares regression.

Missile Proliferation and Complexity

Many complex systems are difficult to examine or model using conventional optimization techniques. The difficulty arises from the enormous size and complexity of the search space. Traditionally, arms procurement and weapons innovation has been seen as the outcome of rational choice and optimization. One meaning of optimization is that every agent selects a unique strategy that dominates every other strategy. If the search space is intractably large, optimization may have no operational meaning. The decision to regard the interactions among nations as a complex system poses deep questions for the received models of rationality.

Alternatively, Chapter 6 simulates the complexity of missile proliferation with computer algorithms known as cellular automata: a two-dimensional square array of identically programmed cells. Although cellular automata are very simplified models, they are capable of mimicking the nonlinear dynamic behavior like thresholds and feedback. The algorithm rules that arm and disarm sites and change range and payloads are derived from empirical regression analysis of Chapter 5. Starting with a random distribution of armed sites among unarmed sites, the lattice system *self-organizes* into clusters of armed and unarmed sites.

Is This Economics?

Is the proliferation of ballistic missiles an economic issue? Obviously not, if the "tight" Chicago priors are taken as definitive. Yet ballistic missile proliferation is very much about economics because the subject is a study of rational choice under restrictions. Classical models of arms racing typically assumes that procurement is mechanistic and a rational response to perceived enemy threats. For instance, the Richardson model of arms racing, arms acquisition is the rational choice given certain constraints with respect to arms production and the reaction of the opponent. While neoclassical economics facilitates the investigation of problems that are treatable by static equilibrium analysis, "it ignores evolution, process, evolution and pattern formation-problems where things are not at equilibrium, where happenstance, where history matters a great deal, where adaptation and evolution might go on forever" (Waldrop, 1992, p. 325).

Greek sophist Zeno, presents an interesting paradox, which illustrates the limitations and inadequacies of static equilibrium analysis. An arrow's flight, which coincidentally follows a ballistic missile trajectory, viewed at any point along its trajectory is stationary. Since the arrow's flight consist of an infinite number of points, each of which is stationary, its movement is an illusion.

Ostensibly, Zeno was trying to show the absurdity of understanding a systems by studying its parts. By focusing attention on the parts separate from the whole, the phenomenon of flight becomes and illusion.

I propose a theory of ballistic missile proliferation based on the principles of self-organizing systems. In a self-organizing system, the order evident in the world – is emergent. Emergent order arises from the interaction among states. This order is not reducible from the actions of one or a few states. Ballistic missile proliferation is a consequence of competitive and adaptive behavior of states. Order emerges from the desire among states to enhance their security vis-à-vis neighboring states. Complex adaptive behavior is of great interest to social science, and especially economics, because it is an effort to explain social and economic phenomena by identifying the preferences of agents.

CHAPTER 2

Game Theory and Missile Proliferation

Game theory is formally a branch of mathematics developed to deal with conflict of interest situations in social science (Zagare, 1984, p. 7). As such, games can improve our understanding of ballistic missile proliferation. Game theory provides an important framework for analyzing the underlying rationales and motives for ballistic missile proliferation. The key assumption of game theory is that the players are rational (or utility maximizers). This simply means that players will act to bring about the most preferred of possible outcomes, given the constraint that all other players are also acting in the same way.[1]

Certain scholars do indeed view missile proliferation as the logical outcome of rational choice. In describing ballistic missile proliferation in the Middle East, Navias (1993, p. 37) contends that each state "...has its own particular motivations and objectives in acquiring ballistic missile systems, as each country's defense planners seek to find solutions to their own particular security dilemmas and threats. It is therefore not unreasonable to assume that in each state a different weight is attached to the various rationales for supporting ballistic missile acquisition."

Considerable scholarship has been made in applying the gaming models to arms racing. As a theory of rational decision making, arms racing gaming models specify how

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[1] Rationality on the part of contemporary proliferants is a hotly contested issue. U.S. policymakers fear that the so-called 'rogue states' may not be susceptible to deterrence as the Soviet Union was during the cold war: An isolated and paranoid North Korea or a religiously motivated Iran or a vengeful Iraq might attack the United States, massive retaliation notwithstanding. Irrationality on the part of these states has become an article of faith for missile defense proponents. Given the inability of these states to adhere to the principles of strategic deterrence, a national missile defense system seems warranted.

players (or countries) should act to achieve their national security goals. Richardson's (1960) models used differential equations to assess the outcome of a two-player arms race. Majeski (1984) and Downs and Rocke (1987) applied game theory to assess the possibility that cooperation will emerge in repeated play of a Prisoner's Dilemma arms rivalry. Lichbach (1990) combined various forms of the Richardson arms racing model with Chicken, Stag-Hunt, Deadlock, and Prisoners' Dilemma, to determine the equilibrium outcome of 2 x 2 game theory arms rivalry models.

In this Chapter, I use four different game-theoretic models to explain the "various rationales for supporting ballistic missile acquisitions". These models are: Chicken, Prisoners' Dilemma (PD), a hybrid of Chicken and PD, I call SSM, and a continuous game model. These games involve countries or players, each of which chooses between two strategies: *cooperate*, C or *defect*, D. In the context of missile proliferation, cooperation and defection may be thought of as "not arm" and "arm," respectively. Players choose their strategy simultaneously and independently in order to maximize their expected payoffs from playing a particular strategy. Since players are also unable to bind themselves to an *a priori* agreement, their actions are non-cooperative. In other words, the players can not write an *a priori* contract that binds them to a particular strategy.

These game theoretic models are abstractions of ballistic missile proliferation in the real world that are meant to capture and convey important aspects of missile proliferation, particularly the intractability of unilateral disarmament. Game theory models also help us understand the some of the underlying motives and rationales for missiles procurement.

These models lay the foundation for much of the subsequent analysis in my thesis. Chapter 3 expands the two-player gaming models into multi-player games. The continuous gaming model serves as the theoretical justification for the regression models of Chapter 5. More importantly, these games show how ballistic missile proliferation is rational response to a state's desire to meet its existing security needs.

Chicken: The Deterrence Game

Deterrence can be defined "as a party's perceived ability to inflict unacceptable casualties on its adversary if the adversary attacks" (Anderton , 1992, p.92). Deterrence theory usually pertains to unitary state actors and focuses on the use of retaliatory threats of force to deter aggression. Operational deterrence employs (1) credible capabilities, (2) clearly communicated threats, (3) credible willingness to carry out threats. Rational choice is central to deterrence theory: Given assumptions (1) – (3), states dissuade "an adversary from doing something it would otherwise want to do so through the means of threats of unacceptable costs" (Price and Tannenwald, 1995, p. 116). This presumes that countries can accurately calculate the costs and gains of their actions.

Chicken, which takes its name from a popular sport with some drivers in the 1950s, has been proposed as a game-theoretic model of deterrence (Brams, 1988). In this game of nerves, rival drivers of two high-speed cars are headed towards one another. Each driver can choose one of two strategies: either to cooperate (C) by turning the car and avoiding a serious head-on collision, or to defect (D) from cooperating by steering straight into the oncoming car. In light of the competitive conditions under which the game is played, it seems safe to assume that the best outcome is for one driver to swerve, while the other remains on course (DC or CD). However, the driver who swerves is labeled the "Chicken", while the racer who remains on course is labeled the "winner". The mutual defection outcome DD- where both drivers remaining steady and crash into one another, is the worst outcome. Mutual cooperation CC, which will save both drivers' lives, is a tie that only proves that both drivers are 'Chicken'.

Chicken has received considerable attention from social scientists who have used its framework to model the interdependent strategic calculations of players attempting to deter an opponent from taking aggressive action against oneself (Brams, 1988, p. 40). The assumptions of Chicken are diagrammed in Table 2.1.

Table 2.1

Outcome Matrix for Chicken

		Player Y	
		C	D
Player X	C	(3, 3) Compromise	*(2, 4)* Y wins, X loses
	D	*(4, 2)* Y wins, X loses	(1, 1) Disaster

Notes. (x, y) = rank of Player X, rank of Player Y)
The cell values refer to ordinal ranked preferences
4 = best; 3 = next best; 2 = next worst; 1= worst
Nash equilibria are in italics.

In this matrix the best outcome is represented by 4, the next best outcome is 3 and so on. These entries represent payoffs to players X and Y. Thus, (4, 2) is the best outcome for Player X and (2, 4) is the best outcome for Player Y. For example, (4, 2) player Y would do worse if he moved to (1, 1) and Player X would do worse if he moved to (3, 3). Unfortunately (3, 3) is not a Nash equilibrium: Player X would do better if he moved to (4, 2) and Player Y would do better if he moved to (2, 4).

The effects that Chicken might have on ballistic missile proliferation directly follow from the car-racing scenario: If one country (say Player X) threatens the other country (Player Y) with ballistic missiles (per assumptions (1) – (3), p. 26), the best response for Player Y is to cooperate, leading to (4, 2). Yet Chicken presents countries with troublesome options: By choosing to arm, a country can "win" prestige and a strategic leverage over its rival but runs the risk of the rival arming; by choosing to cooperate, each can benefit from disarmament, but loose prestige and strategic leverage over a rival.[2]

Saudi Arabia has legitimized its acquisition of *CSS-2* intermediate range ballistic missiles (IRBMs) in general deterrence terms vis-à-vis Iraq and Iran. According to Saudi Prince Bandar bin Sultan, "... once Iran and Iraq not only introduced missiles but used them and we saw the results, we had no option but to match it ..." (Navias, 1993, p. 57). However, Saudi Arabia's neighbors could not be so sure of its intentions. The *CSS-2's* range of 1,500 miles allows the Saudis to strike any country in the Middle East, albeit with low accuracy. Low accuracy means that conventional warheads would be of little use against distant targets in Iran or Iraq. So there is some concern that the *CSS-2* warheads might be non-conventional-presumably nuclear. This speculation is not unfounded. The Chinese developed the *CSS-2* in the 1960s to carry a single 1 – 3 megaton (thermonuclear) warhead and later modified the rocket to carry three warheads each in the 50 – 100 kiloton range (Navis, 1993, p. 27). Although Riyhad has vigorously denied its *CSS-2*s have non-conventional warheads, the stated procurement price of approximately $2.5 billion (1988 dollars) for roughly 60 missiles is in line with the cost of a modern nuclear missile system (Binkley 1994, p. 82).[3]

In March 1988, there were reports that Israel was practicing low-level bombing raids over the Red Sea in preparation for a pre-emptive attack on Saudi Arabia's *CSS-2*s

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[2] Former CIA director William Webster has noted that the deterrent value of ballistic missiles is higher than for manned aircraft (Navias, 1993, p. 11).

arsenal (Navias, 1993, p. 58). Riyhad warned that if attacked, any surviving missiles would be launched at Israel. Unlike Israel's attack on the Osirak nuclear reactor in Iraq seven years earlier, an Israeli raid on the *CSS-2*s would have trigger a major regional confrontation (1, 1).[4] Key Arab nations rallied around Saudi Arabia. Jordan and Syria warned that an attack on Saudi Arabia would be considered an attack on them, while Egypt condemned Israel's 'irresponsible threats.' Table 2.2 diagrams the matrix for the *CSS-2* and the Israeli Raid with Chicken payoffs. This 'mini-crisis' ended without any raids; the Saudis kept the *CSS-2* missiles (4, 2).

Table 2.2

<u>Outcome Matrix for Saudi *CSS-2* and Israel Raid</u>

		Israel (Raid)	
		C	D
Saudi Arabia (*CSS-2*)	C	(3, 3) No Israeli raid Saudis disarm No Saudi retaliation	(2, 4) Israel raids some *CSS-2s* Saudis disarm remaining *CSS-2* No Saudi retaliation
	D	(4, 2) Saudis keep *CSS-2* Israel does not raid *CSS-2* No Saudi retaliation	(1, 1) Saudis keep *CSS-2* Israel raids some *CSS-2s* Saudis retaliate Regional war

<u>Notes.</u> (x, y) = (rank of Saudi Arabia, rank of Israel)
The cell values refer to ordinal ranked preferences
4 = best; 3 = next best; 2 = next worst; 1 = worst
Nash equilibrium outcome is (4, 2) .

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[3] In the early 1980s, Britain negotiated a deal with Lockheed to purchase 100 *Trident D-5* SLBMs $3.2 billion (IIRC, 1984, p. 212). The *Tridents* are much more advanced that the *CSS-2s*. *Trident* SLBMs have star-guided inertial navigational systems, which enables its warheads to carry out counterforce strikes.

[4] In 1981, Iraq's retaliation capability vis-à-vis Israel was limited. Its longest-range missiles, the *Scud B* could not reach Israel. Iraqi manned combat aircraft would need permission from Amman cross Jordan's air space in order to carry out a retaliatory strike. Granting such a request would have undoubtedly brought Jordan into direct conflict with Israel.

In the case of mutual cooperation (CC), the Saudis disarm their *CSS-2s*, the Israelis threaten but do not launch a raid and consequently there is no Saudi retaliation. While mutual cooperation is desirable from a disarmament perspective, it is irrational from a strategic perspective. Given the financial commitment the Saudis made in order to get the *CSS-2s* and the Israelis security concerns and the fact that both countries are technically at a state of war with one another, mutual cooperation seems implausible.

If both countries defect (DD) then the Saudis keep the *CSS-2* missiles and respond to an Israeli raid by retaliating with the surviving *CSS-2s*. Mutual defection is undesirable because it would probably trigger another Middle Eastern war. This outcome would be disastrous for both countries. Alternatively, if an Israeli raid destroys some CSS-2s and Saudi Arabia disarms the surviving CSS-2 arsenal then Israel defects and Saudi Arabia cooperates (CD). In this scenario, the Saudis back down in order to avoid triggering another Middle East war. While (CD) is an Nash equilibria, it does not seem plausible given the financial commitment the Saudis made in order to acquire the CSS-2s. Moreover, cooperating for Saudi Arabia would leave it vulnerable to missile threats from Iraq and Iran.

The logic of deterrence dictates that a state must convince its adversary that it intends to remain (defect) and that the only way to avoid disaster is to back down (cooperate). While Israel's raiding practices were veiled threats against Saudi Arabia's *CSS-2s,* the Saudi threat to retaliate was direct, unambiguous, and very credible. Given the credibility of the Saudis threat to retaliate, coupled with the probability of another Arab-Israeli war, the Israelis maximized their security payoffs by cooperating. Although being exploited was bad for the Israelis, it was not as bad as another Arab-Israeli war.

The Prisoners' Dilemma

Game theory's most distinguished non-cooperative theoretical construct is the Prisoners' Dilemma (PD). In the Prisoners' Dilemma, two suspects are taken into custody. The district attorney separates suspects and tells each one that he has two choices: confess (D) to the crime and thereby implicate the other suspect, or not confess (C) to the crime. If they both confess (DD), each receives a five-year sentence; if neither confesses (CC), both get convicted and spend only one year in jail. If however, one suspects confesses and the other does not (CD or DC), the defecting will be set free for cooperating with the state, while the other 'loyal' suspect gets a ten-year sentence (Zagare, 1984, p. 51).

The 'dilemma' arises from rationality on the part of the two contestants, who find themselves in an awkward situation. Even though both suspects are better off if they both cooperate- CC (each getting one year in jail), the dominant strategy dictates that each player, in pursuing his own selfish ends will defect. Each suspect has an incentive to defect or 'rat' on the other in order to obtain their individually best outcome-freedom. Indeed, the suspects' unconditionally best strategy is to confess to the crime, even though mutual confessions puts both suspects in jail for five years. The best outcome for *both* suspects is for neither one to not confess, in which case each would spend only in one year in jail. However, because the suspects are unable to write an *a priori* contract binding them to mutual cooperation (CC) they each pursue their dominant strategy (DD).

The prisoners' dilemma is illustrated in Table 2.3. Here, each suspect or player has two strategies confess (defect-D) and not confess (cooperate-C).

Table 2.3

Outcome Matrix for Prisoners' Dilemma

		Player Y	
		C	D
Player X	C	(3, 3) Compromise	(1, 4) Y wins, X loses
	D	(4, 1) X wins, Y loses	*(2, 2)* Trap: X & Y loose

Notes. (x, y) = rank of Player X, rank of Player Y)
The cell values refer to ordinal ranked preferences
4 = best; 3 = next best; 2 = next worst; 1= worst
Nash equilibrium is in italics.

The choice of D by both suspects leads to (2, 2) which is Pareto-inferior since it is worse than (3, 3). While mutual cooperation CC yields the best outcome (3, 3) for both players, it is not stable: Player X could do immediately better by switching from C to D, moving the outcome to (4, 1) from (3, 3) and Player Y could do immediately better by unilaterally switching from (3, 3) to (1, 4). Mutual defection DD is the Nash equilibrium for PD because *neither* player could do better by switching strategies.[5] For instance, a unilateral switch from mutual defection (DD) by either player would lead to the cooperator serving a ten years in sentence. Because of this stability, neither player is motivated to depart from DD even though CC is a better outcome for *both* players.

International relations scholars frequently associate the logic of arms racing with that of the prisoners' dilemma (Jervis, 1978; Zagare, 1984; Majeski, 1986; Brams, 1995; Brams, 1988; Stein , 1990). Brams (1985) used the PD model of two nation's weapons

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[5] A Nash equilibrium is an array of strategies, one for each player, such that no player has an incentive (in terms of improving his own payoff) to unilaterally deviate from his part of the strategy array (Kreps, 1996).

acquisition in which there is an interdependent choice of the level of military expenditures.

Given the choice between arming and not arming, all states find arming is a dominant strategy (Stein, 1990, p. 124). States that do not arm run the risk of being exploited by an armed rival. Mutual cooperation (CC) saves states money and lessens the threat of attack but is unstable because it's susceptible to cheating: there is no way to ensure that one's opponent will cooperate. If one state defects the other will do so as well (Stein, 1990, p. 124). States are trapped in mutual defection (DD) because each independently concludes that it is better off arming itself.

What makes the PD model so fascinating is that rationality yields an outcome that is sub-optimal. Irrationality (e.g. rejecting the dominant strategy in favor of cooperating) would yield a highest payoff for both players. Assuming that the end result of an arms race is worse than the situation that existed before the race began, competitive weapons buildups constitute prisoners' dilemmas (Majeski, 1984; Stein, 1990).

Examples of arms rivalries that are PDs abound. Some of the prominent arms racing PDs examined in the literature include: the Anglo-German dreadnaught naval arms race that preceded WW I; The American-British-Japanese naval arms race following WW I; and the U.S. - USSR ICBM deployment in the 1960s and early 1970s.[6] In these arms races, the insecurity of each state compelled it to seek greater security through weapons procurement. But as each state watches it neighbor's power grow, its own sense of insecurity recurs. It then tries all the more to gain ever-greater security with more

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[6] The PD outcomes have been tempered by a series of disarmament measures in which countries promise not to play their dominant strategy of arming. The Washington Treaty of 1923 temporarily suspended the US-UK and Japanese naval arm race. Similarly, the SALT I accord limited the number of launchers

weapons. The result is that each state is trapped in the familiar 'security dilemma': more arms but less security (Herz, 1969, p. 231-232). This type of security dilemma is well known in the literature. Jervis (1993, p. 28) notes that such "threats can set off spirals of counter-threat; the states attempt to increase its security can decrease it; the effort to contain an adversary can create an enemy...". In each of these cases, countries defected to obtain their unconditional 'best' outcomes (4), yet because the opponent did likewise, the they brought the worse outcome (2, 2) upon themselves.[7]

The missile race between India and Pakistan is representative of a Prisoners' Dilemma gaming model. While both countries have had ballistic missile capability since the early 1990s, intermediate-range missile tests in April 1999 marked a major advancement in the military capabilities of both countries. Table 2.4 diagrams the outcome matrix for the Indian *Agni II* and Pakistani *Ghauri II* missile tests.

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available to the superpower. The results of Chapter 3 show that cooperation (disarmament) can emerge without binding states to treaties.

Table 2.4

Outcome Matrix for *Agni II* and *Ghauri II* Missile Tests

		India (*Agni II*)	
		C	D
Pakistan (*Ghauri II*)	C	(3, 3) Pakistan does not test *Ghauri* India does not test *Agni*	(1, 4) Pakistan does not test *Ghauri* India tests *Agni*
	D	(4, 1) Pakistan tests *Ghauri* India does not test *Agni*	(2, 2) Pakistan tests *Ghauri* India tests *Agni*

Notes. (x, y) = (rank of Pakistan, rank of India)
The cell values refer to ordinal ranked preferences
4 = best; 3 = next best; 2 = next worst; 1 = worst
Nash equilibrium is (2, 2).

Both countries are tempted to defect (or test) in order to achieve their 'best' outcome. For India, missiles tests enhance its regional stature and international prestige. India's civilian missile and space rocket programs have become symbols of national achievement (Mc Carthy, 1994).[8] India does not need to long-range missiles to attack Pakistan, for which sufficient advanced aircraft.[9] India's interest in long-range missiles stems more from its desire being a regional power on par with China. As a senior diplomat in New Delhi commented: "India's military expansion is not so much part of a strategic assessment as a view of India's proper place in the world" (Nolan, 1991, p. 86).

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[7] Mutual defection is Pareto inferior since (2, 2) is the worst outcome for both countries.

[8] Both countries have agreed to notify each other prior to test launching missiles. In the PD context of mutual fear and suspicion, it does not take much to arouse and confirm another state's apprehension and thus to stimulate the development of reciprocal images of hostilities (Spanier, 1987, p. 117).

[9] India has developed overwhelming air superiority over Pakistan since the last war between the two countries in 1971. For Pakistan, the *Ghauri* is also counter to India's air supremacy.

The *Agni II*'s 1,500-mile range does put all of Pakistan within its reach, but if based in the far eastern Indian state of Arunachel Pradesh, the *Agni* could reach Beijing.[10]

Three days after the *Agni II* test, Pakistan tested its *Ghauri II* IRBM. Like India, ballistic missiles have a national and religious appeal in Pakistan [11] However, for Pakistan, the *Ghauri* test was mostly intended to demonstrated the country's strategic capabilities and to avoid the exploited outcome (1, 4). Pakistan's missile test also punished India's defection: The *Ghauri II* has payload and range capabilities comparable to the *Agni II*, and can reach all of the Indian subcontinent.[12] The *Ghauri* test essentially put all Indian cities, staging points and air bases under missile threat.

By conducting the missiles tests, India and Pakistan brought the worse outcome upon themselves – a costly and dangerous arms race (CC). Fortunately, the *Agni* and *Ghauri* tests did not trigger a war, nonetheless the missile development advanced the pace of the 'South Asian arms race'. These tests came less than a year after both nations had conducted a series of underground nuclear explosions.[13] Ostensibly, the missile tests were intended to demonstrate the credibility of each country's nuclear arsenal. Possession of the bomb requires a delivery method; ballistic missiles are the most suitable

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[10] Were India to improve the Agni's accuracy, it might be a threat to China's nuclear force. India's effort to develop its own missiles demonstrates the complexity of ballistic missile proliferation: China might take action against what it perceives to be provocation by India. Beijing's Military Academy recommended China re-deploy medium- and long-range missiles against India after its nuclear tests last year. *Reuters* April 9, 1999.

[11] Pakistan has chosen to give its ballistic missiles Arabic names to appeal to both domestic and Arabic audiences as well as highlight its desire to establish an identity and capability separate from India. For instance, the *Ghauri* is named after a legendary Afghan Muslim king who invaded India in the 12th century and defeated the Hindu Prince *Prithvi* in battle. *Prithvi* is the name India gave to one of its own, short-range, missiles. Pakistan's short-range *Haft* missiles is 'deadly' as in the name given to a prophet's sword.

[12] The *Ghauri II* has a range of 1,240 miles and a payload of 2,200 pounds. The *Agni II's* range is 1, 500 miles and has a payload capacity of 2,500 pounds. Both missiles can carry conventional or nuclear payloads.

[13] "Dismay as India starts missile tests," *The Times* (London), April 11, 1999

instrument for this purpose (Binkley, 1994, p. 88). And the *Agni* and *Ghauri* can carry either nuclear or conventional warheads.

India and Pakistan have fought three wars in the past 51 years and their new nuclear status has caused some to fear that another confrontation could escalate into a nuclear war. However for now, the missile tests have embroiled both countries in a fiercely competitive and costly arms race. While neither country intended to embark on a arms race, neither wants to be left behind or exploited. Pakistan's foreign ministry claimed that "Pakistan does not want a nuclear and missile race in South Asia." Yet its engineer and scientists are proceeding with the development of the *Shaheen II*, a more advanced ballistic missiles with a range of 1,430 miles and a nuclear payload capability of 2, 200 pounds.[14]

India faces a similar security dilemma. Following the *Agni* test Indian leaders stated that New Delhi "wants to avoid a nuclear and missile race with its neighbors and to meet its security requirements at the lowest possible levels."[15] Nonetheless, New Delhi broadened its commitment to ballistic missile development after the tests by moving forward with a Sea-Launched Ballistic Missile (SLBM) weapons system.

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[14] "Pakistan test nuclear capable missile," *Los Angeles Times*, April 14, 1999.

SSM Model of Missile Proliferation

In conflict models such as the Prisoner's Dilemma and Chicken actors are unconcerned about the other peoples' security: they get no pleasure or satisfaction from others' happiness or unhappiness (Nicholson, 1994, p. 77). In the PD for instance, each players unconditional best decision is not influenced by the choice of its opponent – therefore there is no interdependence. However, for states in competition, the benefits of their rival are often seen as harmful because they are benefits to an enemy. Pakistan's concentration of population centers and major military installations near the Indian border and lack of territorial depth, saddle it with intractable disadvantages (Nolan, 1991). Consequently, Pakistan viewed India's *Agni* test as a direct threat to its sovereignty and security. While Pakistan's military planning is almost wholly directed at achieving parity with India or avoiding the exploitative outcome (1, 4), Islamabad is also concerned with India's military capability. India is likewise, concerned with the military strength of Pakistan.

I have portrayed these interactions in gaming model I call: "SSM". In this model, depicted in Table 2.5, countries do care about the arming choices of their rival.

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[15] "US resents *Agni* test firing," ***Daily Hindu***, April 11, 1999.

Table 2.5

Outcome Matrix for SSM

		Player Y	
		C	D
Player X	C	(2, 2)	(0, 2)
	D	(2, 0)	*(1, 1)*

Notes. (x, y) = rank of Player X, rank of Player Y)
The cell values refer to ordinal ranked preferences
2 = best; 1; 0 = worst
Nash equilibrium is in italics.

Unlike the prisoners' dilemma game, where players are tempted to defect in order to achieve their 'best' outcome, SSM players are motivated to defect in order to punish a rival or to avoid their worst outcome (0). By defecting against a cooperator (DC) the former only gains the ability to punish the later. In this sense ballistic missiles are truly 'vengeance' weapons.[16] Here, I assume that ballistic missiles (with conventional warheads) are of only marginal military use. As weapons of war, conventional missiles are generally considered to be of limited value on the battlefield. Poor accuracy ensures that most ballistic missiles will have little chance of hitting and destroying desired military targets. Nolan (1991, p. 84) contends that "short-range conventionally armed ballistic missiles are not particularly effective military instruments."

However, against large fixed objects like cities, where accuracy is unimportant, ballistic missiles (even the conventional ones) can be very destructive. Germany launched thousands of *V-2* ballistic missiles at cities in Europe, in a desperate effort change the

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[16] The world's first ballistic missile the German *V-2* was called by 'vengeance weapon' by Hitler. Despite its battlefield potential, the Germans largely used the *V-2* as punishment weapon against European cities.

course of World War II. Between September 1944 and March 1945, 518 rocket hit London causing 9,000 causalities; Antwerp, its other major target of the *V-2* received 1,341 missiles and suffered 30,000 casualties.[17] While the *V-2* gave the Germans a powerful weapon against which the allies had no defense (DC), the missile proved to be inconsequential to the war's final outcome.

The ability to punish a defector can bring about deterrence and thus offers an incentive for an exploited state to defect. Thus the off-diagonal strategies (DC and CD) of SSM are unstable because a cooperating player can improve his expected payoffs by defecting. The SSM game shows that if two countries behave rationally, they will each arm and each will be worse off than they would have been had they both been irrational and cooperated. Mutual defection (DD) is the Nash equilibrium because neither player can improve his expected payoffs by unilaterally cooperating. While mutual defection can lead to mutual deterrence, it can also trap states in an arms race or leave war combatants stalemated.

The Iraq-Iran war became the first war in history where combatants fired ballistic missiles against one another. The role surface-to-surface missiles played in this war is a subject that has generated much controversy. While some scholars have attributed Iran's willingness to negotiate a settlement to end hostilities to Iraq's threat to strike Terhran with chemically tipped missiles, others have pointed out that ballistic missiles did not permit Iraq to acquire its territorial claims to Iran's portion of the Shatt waterway. Table 2.6 diagrams outcome matrix for ballistic missiles in the Iraq-Iran conflict.

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[17] The *V-2* rocket was the first supersonic guided missile. The 13-ton rocket struck its targets as speeds of 2,386 mph thus arriving without warning *(The Atlas World of Warfare: Military Innovations That Changed History)*.

Table 2.6

Outcome Matrix for the Iraq-Iran War

		Iraq (*Al Husayn*)	
		C	D
Iran (*Scud B*)	C	(2, 2) (2, 2) ned Iran unarmedned Iraq unarmed	(0, 2) Iran unarmed Iraq – *Al Husayn*
	D	(2, 0) Iran - *Scud B* Iraq unarmed	(1, 1) Iran – *Scud B* Iraq – *Al Husayn*

Notes. (x, y) = (rank of Iran, rank of Iraq)
The cell values refer to ordinal ranked preferences
2 = best; 1 = next best; 0 = worst
Nash equilibrium is (1, 1).

At the beginning of the war in 1980, Iraq's missile arsenal consisted of *Scud-B* missiles and *FROG* rockets; Iran did not have ballistic missiles at this time (CD). As originally configured, the *Scud-B* with a range of 180 miles, could not reach any of Iran's major cities from Iraqi territory. The *FROGs* are unguided and limited to a 40 mile striking range. The poor accuracy of the *FROGs* ensured that they had little chance of hitting Iranian army positions near Ahwaz and Dezful (Navias, 1993). Consequently, the tactical effect of these missiles was minimal. By 1982, Iraqi missiles and rockets were re-directed against Iranian border towns of Ahwaz, Borujerd, Dezful, Isfahan and Khorramabad. Despite having fired a total of 140 *Scuds* and 67 *FROG*s at Iran in the first five years of the conflict, Iraq gained no major concessions from its missile campaigns (Cordesman and Wagner, 1990, p. 495-506). In fact, by 1982 Iraq had withdrawn from much of its occupied Iranian territory (Navias 1993, p. 133).

Recognizing the futility of these missile strikes, Iraq embarked on a plan to attack Iran's larger urban centers east of the Zagros Mountains. Again, the intention of the plan was not to achieve a decisive military victory but to punish civilians and thereby weaken the Iranian government's resolve to continue fighting. In 1984, Iraqi Lieutenant General Amer Rahsid al Ubeidi noted:

> " The Persian people had been deluded by their leaders, who told them the war would never affect them. The blows we inflicted at the border were absorbed and never reached the interior. We wanted to bring the war to the people of Persia, to make them realize the folly of their leaders. And only ballistic missiles offered us this opportunity."[18]

In order to hit major Iranian population centers, the Iraqis extended the *Scud-B*'s range to 375 miles – creating the *Al Husayn*. The *Al Abbas* another *Scud B* upgrade, extended Iraq's reach to 550 miles. Iraq fired 189 of these modified *Scud* missiles at Terhran during the "War of the Cities" campaign in 1988. Specifically, Iraq fired 135 missiles at Terhran, two at Karaj, 23 at Qum, three at Shiraz and four at Tabriz between 29 February and 20 April 1988 (Cordesman and Wagner, 1990, p. 41). Baghdad employed these missiles explicitly in order to terrorize the Iranian capital and bring public pressure on the Iranian government to end the war (Navias, 1993, p. 136).

Initially, Iran's missile arsenal was more limited than Iraq's. Thanks to an arms embargo, the Iranians did not obtain ballistic missiles until 1985. Navias (1993, p. 51) contends that Iran began acquiring ballistic missiles initially in response to Iraqi missile attacks:

> "... the Iraqi missile attacks galvanized the Iranians to acquire ballistic missiles. This was because they must have been impressed ... by the effect the missiles had on their civilian population. Furthermore, the Iranians believed that the one method for deterring future missile attacks was their own capability to reply in kind."

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[18] Quoted in Navias (1993, p. 50)

Although Iran's missiles had shorter ranges than Iraq's *Al Husayn*, the distance needed strike major targets in Iraq is also shorter – Baghdad is barely 95 miles from the Iranian border; Basra, Iraq's second largest city is less than 15 miles from the Iranian border.

After 1985, both countries routinely fired ballistic missiles at one another in what ultimately became a three-year stalemate (1, 1). During the 'War of the Cities' campaign in 1988, Iran and Iraq fired hundreds of missiles at each other major cities in an effort to get the other side to surrender. Although both sides suffered from each others' missile attacks, the *Al Husayn* strikes against Tehran led to mass evacuations of that city in March and April of 1988.[19] While many link Iran's subsequent acceptance of UN Resolution 598 to the Iraqi missile attacks, others have pointed out that the *Al Husayns* were only decisive because Iran was already near collapse. Mc Naughter (1990, p. 15) notes that Iran's economy and populace were exhausted from 7 years of war and that "given these circumstance it is arguable that Iraqi bombers would have produced much the same result as Iraqi missiles ..."

Ballistic missiles secured no military gains for either side: Iran did not succeed in its war objective of overthrowing Saddam Hussein and Iraq did not reclaim its rights to the entire Shatt waterway that separates it from Iran. Although the military significance of ballistic missiles is questionable, neither Iraq nor Iran can afford to unilaterally disarm and risk of being exploitation. The wartime motivation for ballistic missile carried over into the post-war period and trapped both countries in a missile arms race. Following the

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[19] Aharon Levran (1993) contends that "Iran's reaction to the missile attacks appear to have been generated less by casualties it suffered than by strategic and psychological shock." (cited in Navias, 1993, p. 136).

end of the war, Iran and both expanded the quantity and quality of their respective missile forces-with an eye to future employment against one another (Navias, 1993).

For Iran, the war entrenched Tehran's determination to avoid being exploited because of the international arms embargo. Indigenous ballistic missile production offers Iran a way around its international arms embargo. The Pentagon believes Iran will become mostly self-sufficient in the production of medium range ballistic missiles by 2003.[20] Iranian ballistic missiles are an attractive alternative to manned aircraft. Ballistic missiles provide Tehran with a means to carry out long-range military missions without having to train pilots and maintenance crews, which are extremely scarce.[21] Tehran is currently developing a next-generation *Shahab-4* missile with a range of 1,240 miles, which means it could select targets as far away as central Europe. The *Shahab-3* debuted in July 1998, in a 800-mile flight test.

For Iraq the war reinforced the necessity of a missile deterrence vis-à-vis Iran. In 1989, Iraqi foreign minister Tariq Azziz justified development of the 2000 km *Tammuz* ballistic missiles in such terms:

> "Iraq is still threatened by Iran ... consequently we will do our best to acquire the necessary defense equipment in order to defend our country in case the other side contemplates the resumption of hostilities." [22]

The war also justified the use of ballistic missiles in war. The Iraqi missile strikes during the 1990-91 Persian Gulf War in and of themselves were of little military consequence, but led to a massive diversion of coalition military power to target missile installations and missile launchers in Iraq. This diversion took some pressure off of Iraqi

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[20] "Iran has successfully tested a missile capable of striking targets in Israel." *Los Angeles Times*, July 24, 1998.

[21] Nolan (1991) notes that the Iranian government's deep mistrust of professional military personnel, in particular the Air Force, is also a motive for keeping ballistic missiles.

ground forces but it was not sufficient enough to win the Iraqis any significant tactical concessions.

Although Iraq's missile program has been stunted by a strict UN arms embargo, Baghdad remains committed to ballistic missiles. After the 1991 Persian Gulf War, Iraq began work on the *Al Samoud* missile.[23] Iraq first tested that missile in 1997 under supervision of the previous team of international inspectors, which sought to ensure that the missile remained within the under 95 miles range restriction the United Nations imposed on Iraq after the Persian Gulf war in 1991. On July 2, 2000, Iraq conducted its eighth test flight of the *Al Samoud.* Several observers viewed the testing as evidence that Iraq was still working to perfect its ballistic missile technology, which could be adapted to missiles with a longer range. Iraq's missile program intensified fears in Iran that President Saddam Hussein may be covertly working on, though not testing, longer-range missiles. The Pentagon claimed in early 1998 that several dozen missiles remained hidden from UN weapons inspectors. These mostly include *Al-Husayn* missiles plus a few *Al-Abbas* missiles.[24] Less than two weeks after the *Al Samoud's* eighth test, Iran conducted the second flight test in two-years of its *Shahab–3* ballistic missile. Iran's official state broadcast said the test was in line with Iran's "policy of strengthening its defense capability on the basis of the principle of deterrence."[25]

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[22] FBIS – NES, December 14, 1989

[23] The missile is believed to be a variant of the Soviet-era *SA-2*, the type of surface-to-air missile that shot down the *U-2* spy plane flown by Francis Gary Powers over the Soviet Union in 1960.

[24] "Iraq's Secret Scuds" *The Times* (London). February 11, 1998.

[25] "Iran Test Ballistic Missile" *Los Angeles Times* July 15, 2000.

Continuous Model of Proliferation

While the aforementioned gaming models help explain the behavior of a two-player arms race, they do not address the impact strategic choices might have on states other than a country's the primary opponent.[26] Ballistic missiles, like most weapons, are not country specific. Palevitz (1990) and Nolan and Wheelon (1990) consider proliferation the result of countries responding to threats from various neighboring states. For instance, it is generally recognized that Saudi Arabia's *CSS-2* intermediate range ballistic missiles (IRBM) were intended to deter Iran, yet its 1, 500 mile range allows Jeddah to target all of the Middle East, much of the Indian subcontinent, Central Asia, and Southern Europe.[27] Although, India's *Agni II* IRBM is meant to deter Pakistan, their ability to threaten Saudi Arabia is in part response to Saudi Arabia's *CSS-2s*. Iran's *Shahab-3* is no less troublesome: This 800-mile IRBM allows Iran to strike all of Israel, all of Saudi Arabia, most of Turkey and the tip of Russia.

The problem with long-rang missiles such as the *CSS-2* is not the desire for better security on the part of the Saudis, but a procurement decision that inadvertently threatened countries other than Iran (e.g. Israel and India). Even though arms acquisitions are typically justified as enhancing security against an existing or potential threat, ballistic missile acquisition might actually erode rather than enhance security.

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[26] Jervis (1978, p. 181) notes that " ... arms sought to only secure the status quo-may alarm others and others may arm, not because they are contemplating aggression, but because they fear attack from the first state." Thus, in trying to increase one's own security one can actually decrease it.

[27] The significance of the countries within range of the *CSS-2* should not be lost. The ability of the *CSS-2* to hit targets in the Soviet Union as well as India, probably weighed favorably in Beijing's decision to sell Saudi Arabia its retired missiles. Moreover, the *CSS-2* counters the India's *Agni*, which can target much of the Arabian Peninsula. Nations have attempted to limit the externality missile ranges have neighboring states though names. In October 1990, Saddam Hussein announced the existence of the 750 km *Al Hajira* ('the stone') ballistic missile following the death of Palestinian demonstrators on the Temple Mount.

The response to missile threats can include missile innovations. Countries already armed with missiles have increased their missile ranges and/ or payloads when faced with additional threats (e.g. Pakistan and India). Consequently, the dichotomous choices gaming models over simplifies a key aspect of ballistic missile proliferation. In reality, countries can choose between arming and disarming as well as the number of missiles, range and payload capability.

In this section, I denote the expected security payoff from ballistic missile procurement as Π, which is assumed to be continuous and have nice differentiability properties. This model intentionally parallels two competitive firms engaged in profit-maximizing activities.[28]

The Continuous Model

Suppose that rival countries *i* and *j* compete with one another though the number of missiles (m_i, m_j) they deploy. The demand for missiles, q_i in country *i* against its rival, country *j*, can be written as:

$$q_i = D(m_i, m_j) = 1 - bm_i + dm_j \tag{2.1}$$

with $b \geq d \geq 0$. Equation (2.1) is in the spirit of the arms racing model put forward by Richardson (1960): The coefficient d measures a nation's reaction to its opponent's missiles while the b coefficient measures each nation's reaction to its own armament. The b coefficient might be interpreted as a satiation coefficient: The more missiles a nation

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[28] Just as firms that do not pursue profit-maximizing strategies will go bankrupt, so too will states disappear that do not pursue self-protective strategies will disappear (Waltz, 1979).

has, the less is its demand for additional missiles.[29] A 'security dilemma' arises from the fact that *J* countries are threatened by country *i*'s missiles and arm in response. Thus by arming to offset country *j* missile threat, country *i*'s security is compromised by threats from *J* armed countries. If $\mathbf{m}_i$ can target *J* nations the expected security payoff to country *i*, Π^i can be written as:

$$\Pi^i = (\mathbf{m}_i - f(J))\,(1 - \mathbf{bm}_i + \mathbf{dm}_j) \tag{2.2}$$

Country *i*'s expected security payoff, is lowered by the fact that inadvertent threat of its missiles on *J* other armed nations. The term $(m_i - f(J))$ measures the reduction in country *i*'s security that arises from the defection of *J* countries. The counter missile threats from *J* countries is embodied in the term $f(J)$, which is a function that increases as *J* increases. The first-order conditions are.

$$1 + \mathbf{dm}_j + f(J)\mathbf{b} - 2\mathbf{bm}_i = 0 \tag{2.3}$$

The pure-strategy Nash equilibrium is unique and symmetric:

$$\mathbf{m}^*_1 = \mathbf{m}^*_2 = (1 + f(J)\mathbf{b})/(2\mathbf{b} - \mathbf{d}) \tag{2.4}$$

Therefore

$$\Pi^* = [(.) - fJ)][1 - \mathbf{b}\,(.) + \mathbf{d}\,(.)] \tag{2.5}$$

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[29] Richardson called these "fatigue and expense" coefficients.

where (.) denotes the right-hand side of equation (2.4). A country's optimal security Π^* will decline as J increases or more nations fall within the range of its missiles.

Equation (2.5) says that the number of missiles is positively related to the number of armed neighbors. Unfortunately, there is no consistent data series that accurately enumerates the number of ballistic missiles for the countries of interest. In Chapter 5, I develop a discrete choice logit model that explains the probability of defection with the number of defecting neighbors. Chapter 5 also explains the variation in ballistic missile ranges and payloads across countries with a similar set of explanatory variables.

CHAPTER 3

Approximation of Nash Equilibrium in Multi-Player Games

A two-strategy (either defect or cooperate) game repeated *n* times is much more complex than the single shot game because there are 2^{n+1} strategies for each player in the *n*th round. As *n* increase, so does the number of strategies. The problem of the iterated multiperson game is the immense number of possible strategies. Arriving at a Nash equilibrium involves a search for the *best* strategy in a massive set of possibilities.

The Peter Albin (1998) proposes an interesting method that plausibly escapes the intractability of multi-player games. He uses a two-dimensional cellular automaton to model Schelling's (1978) multiperson prisoners' dilemma (MPD) as a repeated *N*-person game.[1] Here, agent rules do operate identically to Schelling's micromotived procedures, however, a rational player is allowed to consider the systemic as well as local consequences of her actions.

In Albin's MPD, player payoffs are determined in a neighborhood, for a local subgame involving *n* players, where *n* is much smaller than *N*. The neighborhood is restricted to the eight nearest players, whose information sets overlap to form the full *N*-player system. Consequently, all players are indirectly connected through neighborhood overlaps. These lattice overlaps allows for micro-level initiated actions to propagate throughout the entire system.

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[1] Cellular automata are discrete, spatially homogeneous, locally interacting dynamical systems of very simple construction (De Sales, Matins, and Moreira, 1997). The programming code for the cellular automata simulations experiments is written in C programming language. In each period of a simulation, each cell is characterized by a certain state. The state of the cell in the next period depends on the current state of the cell as well as state of its nearest neighbors. The cellular automata advances through time with cells synchronized to common periodic external clock (Albin, 1998, p. 16). Despite their simple

Albin's MPD simulations includes over 65, 000 fully rational players who seek to improve expected gains from those associated with universal defection in games with prisoners' dilemma payoff structures. Players using game-theoretic reasoning to assess payoff prospects vis-a-vis *n*-persons. No intractability is encountered when players are restricted to the information sets of their eight nearest neighbors.

In the MPD, a cell or cellular automaton represents each player in a 256 x 256 square lattice. The neighborhood of the *i*th cell consist of the eight orthogonal and diagonal adjacent cells-that is those to N, NE, E, SE, S, SW, W, and NW of it. This neighborhood designation and is specified for all cells in the lattice and is shown in Figure 3.1

NW	N	NE
W	C	E
SW	S	SE

Figure 3.1 Cellular Automata Neighborhood Structure.

Opposite edges of the 256 x 256 square lattice are wrapped around and joined to form a cylinder and the ends of the cylinder are joined to form a torus. This torus construction is often referred to as a 'periodic boundary' condition. Figure 3.2 diagrams periodic boundary conditions. Here, the strategies in column 9 are equated to those in column 0 and the strategies of column 1 are equated to those in column 10. Similarly, the strategies of row J are equated to the strategies of row A and the strategies of row K are equated to the strategies of row B.

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construction, cellular automata can evolve into ordered states with complex structures. Chapter 6 discusses cellular automata in greater detail.

	0	1	2	3	4	5	6	7	8	9	10
A	C	C	C	C	C	C	C	C	C	C	C
B	C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C	C
D	C	C	C	C	C	C	C	C	C	C	C
E	C	C	C	C	C	C	C	C	C	C	C
F	C	C	C	C	C	C	C	C	C	C	C
G	C	C	C	C	C	C	C	C	C	C	C
H	C	C	C	C	C	C	C	C	C	C	C
I	C	C	C	C	C	C	C	C	C	C	C
J	C	C	C	C	C	C	C	C	C	C	C

Figure 3.2 Periodic Boundary Conditions. The strategies in column 1 are equal to the strategies in column 9; the strategies in column 10 are equal to the strategies column 0; the strategies in row A are equal to the strategies in row I and the strategies in row B are equal to the strategies in row J.

Prior to time *t*, each player separately and without negotiation with other players, draws information from its eight neighbors and selects the single-period action: defect or cooperate. A players decision to cooperate or defect holds for the period *t* vis-à-vis the eight players in its neighborhood.

The lattice simulation proceeds though time deterministically, with each player adhering to a fixed set of rules for cooperating or defecting. The rules for selecting defect (D) or cooperate (C) in the next period are based on the number of neighbors who have cooperated or defected in the previous period.

Albin's MPD players defect and cooperate according to rules called LIFE. In LIFE, a previous defector continues to defect if surrounded by two or three defectors; a previous cooperator with exactly three defecting neighbors, defects; in all other cases cooperation is played. LIFE rules are impersonal in that they do not distinguish which of the player's eight neighbors cooperated or defected. LIFE is considered a 'trigger transient rule' because every player's choice strategy is triggered by the choice strategies of its *n*-neighbors. Alternatively, the *Wiseguy* rule specifies always defecting against all neighbor actions, while the *Goodguy* rule specifies always cooperating against all neighbor actions. Albin conducts several cellular automata experiments involving these aforementioned rules.

Players use game-theoretic reasoning to assess expected payoff prospects. Payoffs to player *i* are given by the 2 x 2 prisoners' dilemma (PD) matrix shown in Table 3.1. The players total payoff in the neighborhood subgame is the sum of the payoffs with the eight neighbors. The rows in the right-hand portion of the table give the total payoff to player *i* at time *t* for the actions C and D. Thus, universal cooperation corresponds to the entry C, 8 and yields a payoff of 72. Universal defection corresponds to D, 0 and yields an expected payoff of 8.

Table 3.1

Payoff in Prisoners' Dilemma Multiperson Sub-Sub Games and Subgames

			Subgame Number of Cooperators (Defectors)								
Sub-subgame Prisoners' Dilemma			0 (8)	1 (7)	2 (6)	3 (5)	4 (4)	5 (3)	6 (2)	7 (1)	8 (0)
SSM	C	D	MPD Payoffs								
C |	[9, 9]	[1, 10]	8	16	24	32	40	48	56	64	72
D |	[10, 1]	[2, 2]	16	24	32	40	48	56	64	72	80

Notes. The number in parenthesis corresponds the number of defecting neighbors.

The expected subgame payoffs in Table 3.1 are calculated using simple arithmetic. The expected payoff for cooperating with five cooperators and three defectors in its neighborhood is: 9x5 + 3x1or 48. The expected payoff to defecting with five cooperator and three defectors is: 10x5 + 3x2, or 56. The right side of Table 3.1 shows that defection strategy, D dominates cooperation C for all subgames because the payoffs to D, noted D', exceed the payoffs to C, noted C'. (The expected payoffs to all strategy will be denoted with a prime, henceforth). Thus, in single play, the universal defection strategy is a Nash equilibrium.

In repeated play with no discounting, player *i* would select D unless there is an alternative P* that would support and equilibrium superior to universal defection. Albin contends that the P* strategy exists if it satisfies the following three conditions:

Condition 1: *Global payoff incentive*. The payoff P*' to P* must exceed D'

$$P^{*\prime} > D'$$

Condition 2a: *Local defection disincentive*. If P* is the best reply strategy for a rational player confronting *N*-1 players playing P*, it must at least yield an expected payoff P*' equal or greater than the payoff to repeated defection against the *N*-1 players adhering to P*. This can be expressed as:

$$(D_k \mid P_j = P^*)' \leq ((P_k)^* \mid P^*))'$$

$(D_k \mid P_j = P^*)'$ is the expected payoff to the *k*th player who defects repeatedly against *N*-1 players adhering to P* and $((P_k)^* \mid P^*))'$ is the expected payoff *k*th player who plays P* given that *N*-1 player are adhering to P*.

Condition 2b: Analogously, $((P_i)^* \mid D_k)'$ is the expected payoff to player *i* who plays P* conditional on all other *k* players defecting ($k \neq i$). To insure the that the reactions of the P* adherents in disciplining defectors does not result in expected returns below that of D', Albin specifies:

$$(P^* \mid D_k)' > D'$$

While these three conditions 'screen out' continued defection as the best strategy to P*, they are insufficient to criteria for declaring P* as the universal best strategy. In other words, Conditions 1, 2a, and 2b do not account for some "saboteur" strategy P** which is better than P* but might undermine equilibrium or a 'superior' strategy P*** which is a better reply than P* and also sustains equilibrium. This limitation forces a weakening of the standard Nash test for identification of the 'best' reply strategy. Full strategic analysis requires examination of complexity properties that are beyond the scope and intention of this chapter. Nonetheless, we can make considerable progress in resolving multi-player games without the strong Nash test.

In search of a P* strategy, Albin conducts the following four experiments:

(1) exclusively 65, 536 LIFE players;

(2) 65, 519 LIFE and 17 *Wiseguy* players;

(3) 65, 518 LIFE and 18 *Goodguy* players; and

(4) 65, 492 LIFE, 26 *Wiseguy*, and 18 *Goodguy* players.

LIFE, *Wiseguy*, and *Goodguy* players choose a strategy for each time period in accordance to their designated rules. Albin begins his simulation experiments by randomly allocating defectors to the lattice. The initial proportion of defectors range from 20% to 90% of all players. However, after approximately 50 time periods, the number of remaining defectors approaches a limiting value. The system reaches a final configuration or stable configuration after several thousands of time periods (corresponding to hundreds of billions of sub-subgames). Stable number of defectors in small clusters characterizes the final configuration. In the final configuration, defectors account for approximately 3% of the total number of players. Payoff expectations (shown in Table 3.2) are calculated for the representative final configuration in each of the four experiments. The experiments show that the LIFE strategy supports an equilibrium superior to universal defection because the expected payoffs to LIFE satisfy Conditions 1, 2a, and 2b.

Table 3.2

Payoff Values to Different Strategies When LIFE is Played in Multi-person Prisoners Dilemma (MPD)

Experiment	**Players**	**LIFE (Payoffs)**	***Wiseguy* (Payoffs)**	***Goodguy* (Payoffs)**	**Number of Players**
1.	**LIFE**	70.41			Cooperators=63,682
					Defectors=1,854
2.	**LIFE**	69.55			Cooperators=62,641
					Defectors=2,878
	Wiseguys		64.94		Wiseguys=17
3.	**LIFE**	70.66			Cooperators=63,583
					Defectors=1,936
	Goodguys			64.22	Goodguys=18
4.	**LIFE**	70.34			Cooperators=63,582
	Wiseguys		69.77		Defectors=1,910
	Goodguys			70.15	Goodguys=26
					Wiseguys=18

Notes: The entries give estimates of the expected value of a strategy in MPD as calculated from simulation trajectories for all 65,536 players. For instance, in the first experiment, of the 63, 682 cooperators 57,538 had no defecting neighbors, 2626 had one defecting neighbor; 2925 had two defecting neighbors; 288 had three defectors; 104 had four defectors; and 198 had five defectors. The same experiment yielded 1854 defectors 284 of who had one defecting neighbor; 932 with defecting neighbors; 632 with three defecting neighbors; and six with four defecting neighbors. The expected payoff of all 65,536 players in Experiment 1 is 70.41 and was calculated by multiplying MDP payoffs in Table 3.1 by the corresponding numbers of players pursing the a particular strategy adding these values together and dividing by the number of players: (57, 538 x 72 + 2626 x 64 + 2929 x 56 ... + 284 x 72 + 932 x 64 ... + 6 x 48) / 65, 536 = 70. 41.

The average payoff to LIFE is 70. 14 exceeds the D' value of 16. Thus a player who plays LIFE would see Condition 1 satisfied (e.g. P*' > D'). To test LIFE against Conditions 2a and 2b, a small number of agents were randomly selected to play *Wiseguys*. Additional trials include LIFE players mixed with a small number *Goodguys* and a mixture of all three-player types. In each of these three remaining experiments, Conditions 2a and 2b are satisfied (√). That is the expected payoffs to the *k* players always defecting or always cooperating is *less* than LIFE but *greater* than D'.

Condition 1: *Global payoff incentive*. The payoff P*' to P* must exceed D'

$$P^{*\prime} > D'$$

√ Experiment 1: $70.41 > 16$

Condition 2a: *Local defection disincentive.*

$$(D_k \mid P_j = P^*)' \leq ((P_k)^* \mid P^*))'$$

√ Experiment 2: $64.95 < 69.55$
√ Experiment 3: $64.22 < 70.66$
√ Experiment 4: $69.77 < 70.34$ and $70.15 < 70.34$

Condition 2b: *Local defection disincentive.*

$$(P^* \mid D_k)' > D'$$

√ Experiment 2: $69.55 > 16.00$
√ Experiment 3: $70.66 > 16.00$
√ Experiment 4: $70.34 > 16.00$

My replication of Albin's experiments involves perturbing a system of 120 players in a 11 x 11 square lattice with an initial shock of randomly distributed defectors. Prior to time *t*, each site separately and without negotiation with other sites selects the single-period action: Defect (arm with missiles) or Cooperate (unarm). The Multi-Player Game (MPG) rules or strategy is:

(1) If any site (armed or unarmed) is surrounded by 0, 1, 2, or 3 unarmed sites in period *t*, it will be unarmed in the next period *t*+1.

(2) If a cell has *exactly* four neighbors in period *t*, its status will not change in the next period.

(3) All other sites will defect in the following period *t*+1.

The MPG rules are based on the empirical regression model results in Chapter 5, (Equation (3)) which explains ballistic missile proliferation (the dependent variable) with the eight nearest-neighbor missile threats (independent variables).

The advantage of replicating Albin's scholarship is that it allows us to examine the MPG rules against various models arms racing and missile proliferation presented in Chapter 2. The three game theoretic models considered are : Chicken, PD, and SSM. With the exception of Chicken, defection is the dominant strategy for these games. Applied to the context of missile proliferation, SSM and PD suggest that all countries would defect and arm with ballistic missiles. However, in reality, not all countries do have ballistic missiles. In fact, most countries have chosen to cooperate. The absence of universal defection in the real world implies that countries may be playing an alternative strategy P* superior to D. Albin's work gives us a means of determining if the P* strategy supports an equilibrium superior to universal defection. In our case, the P* strategy is defined by the MPG strategy.

In the two-person Chicken (deterrence) model of missile proliferation, the outcomes (D,C) and (C,D) are Nash equilibria rather than universal defection. Conditions 1, 2a, and 2b therefore do not apply. Nonetheless, we can check if the MPG strategy is capable of sustaining an equilibrium superior to universal defection in Chicken.

One-Period Payoffs

The player's expected payoff is the sum of the neighborhood subgame payoffs in sub-subgames with it eight nearest neighbors. The payoff to sub-subgames are calculated identical to Albin (1990) and summarized in Table 3.3. If, for instance, an *armed* cell has *three* defecting neighbors and *five* cooperating neighbors, its SSM expected payoff would be: (3x1) + (5x2) or 13.

Table 3.3 shows that defection, D is the dominant strategy for the SSM and PD subgames because the payoffs to D meet or exceed the payoffs to cooperation, C in every case. Defection, however, is not the dominant strategy for Chicken. Here, the payoffs to cooperating exceeds the payoffs to defecting when a cooperating player is confronted by 5 or more defectors. This makes intuitive sense given the disastrous outcome that would arise from mutual defection. The more defectors a cell has, the greater are its payoffs to cooperating against a majority of its neighbors. However, as the number of cooperators falls, the expected payoff to cooperating falls while the expected payoff to defecting rises. A threshold between cooperation and defecting occurs when exactly *four* neighbors defect. Here, the payoffs for either strategy is the same, 20. At the threshold, Chicken players are indifferent to either strategy. With less than four defecting neighbors, Chicken players are better off risking defection. It is perhaps gratifying to observe that the MPG strategy accords to dominant strategies of Chicken.

Table 3.3

Payoffs in Chicken, SSM, PD, and Sub-subgames and Subgames

			Subgame								
Sub-subgame			Number of Cooperators (Defectors)								
			0 (8)	1 (7)	2 (6)	3 (5)	4 (4)	5 (3)	6 (2)	7 (1)	8 (0)
Chicken	C	D	Multi-Player Chicken (MC)								
C	[3, 3]	[2, 4]	16	17	18	19	20	21	22	23	24
D	[4, 2]	[1, 1]	8	11	14	17	20	23	26	29	32
SSM	C	D	Multi-Player SSM (MSSM)								
C	[2, 2]	[0, 2]	0	2	4	6	8	10	12	14	16
D	[2, 0]	[1, 1]	8	9	10	11	12	13	14	15	16
PD	C	D	Multi-Player Prisoners' Dilemma (MPD)								
C	[3, 3]	[1, 4]	8	10	12	14	16	18	20	22	24
D	[4, 1]	[2, 2]	8	9	10	11	12	13	14	15	16

Notes. The numbers in parenthesis are the number of defecting neighbors.

Albin's *Wiseguy* and *Goodguy* strategies have important analogues in the context of ballistic missile proliferation. A *Wiseguy*, is a player who always arms, might correspond to the so-called "states of concern" (formally titled the "rogue-states"): North Korea or Iran. The *Goodguy*, a player who never arms, might correspond to countries like Japan, Switzerland or Lebanon. What impact do such 'invading' strategies have on a system of MPG players in achieving equilibrium? How do the payoffs to *Wiseguy* and *Goodguy* strategies compare to MPG'.

To address these issues, I conducted four experiments. In the first experiment, sixty-one cooperators (C) and sixty defectors (D) were randomly allocated to a square lattice shown in Figure 3.3. Adhering to the MPG strategy, the system organize itself into zones of cooperation and defection. Figure 3.4 shows the final configuration of the lattice. In the final configuration, the number of defectors and cooperators is stable.

Figure 3.3 Experiment-1:Initial Lattice Configuration

D	C	**D**	C	**D**	C	C	**D**	**D**	C	**D**
C	**D**	C	**D**	C	**D**	**D**	C	**D**	C	C
C	**D**	C	**D**	C	C	**D**	C	**D**	C	C
D	C	**D**	C	C	**D**	**D**	C	**D**	C	C
C	**D**	C	C	C	**D**	C	C	C	**D**	**D**
C	C	**D**	C	**D**	C	C	C	**D**	C	**D**
C	**D**	C	**D**	C	C	C	**D**	C	C	C
D	C	C	**D**	**D**	C	C	C	**D**	C	**D**
D	C	**D**	C	**D**	C	**D**	C	C	**D**	C
D	C	C	**D**	C	**D**	**D**	C	C	C	**D**
C	C	**D**	C	**D**	**D**	C	**D**	**D**	**D**	C

Figure 3.4 Experiment-1: Final Lattice Configuration

C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C
C	C	C	**D**	**D**	**D**	**D**	C	C	C	C
C	C	**D**	**D**	**D**	**D**	**D**	**D**	C	C	C
C	**D**	**D**	**D**	**D**	**D**	**D**	**D**	C	C	**D**
C	**D**	**D**	**D**	**D**	**D**	**D**	C	C	C	**D**
C	C	**D**	**D**	**D**	**D**	**D**	C	C	C	C
C	C	**D**	**D**	**D**	**D**	C	C	C	C	C
C	C	C	**D**	**D**	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C

In the final configuration there are 87 cooperators and 34 defectors. The expected payoff to the 121 players is 18.69 when the sub-subgames is Chicken. The Chicken payoff exceeds the universal defection value of 8. Thus, the MPG strategy satisfies Condition 1. When the sub-subgame is SSM, the expected payoff is 13.13, which is greater than universal defection payoff of 8. Accordingly, the MPG strategy satisfies Condition 1 for the MSSM subgame. Condition 1 is also met when the MPD subgame is played because the expected payoff is 21.27, which also exceeds the universal defection payoff of 16. These results are summarized in Table 3.4.

Table 3.4

Experiment-1: Payoffs Values of Chicken, SSM and MPD

Defecting Neighbors	0	1	2	3	4	5	6	7	8		
Cooperators	51	14	12	10	0	0	0	0	0	87	
Defectors	0	0	0	1	11	2	2	5	13	34	
Total Cells										121	
	Multi-Player Chicken MC									MPG' Expected Payoff	D'
Chicken											
C D											
C [3,3] [2,4]	24	23	22	21	20	19	18	17	16		
D [4,2] [1,1]	32	29	26	23	20	17	14	11	8	**18.69**	**8**
	Multi-Player SSM MSSM									MPG' Expected Payoff	D'
SSM											
C D											
C [2,2] [0,2]	16	14	12	10	8	6	4	2	0		
D [2,0] [1,1]	16	15	14	13	12	11	10	9	8	**13.13**	**8**
	Multi-Player Prisoners' Dilemma MPD									MPG' Expected Payoff	D'
PD											
C D	24	22	20	18	16	14	12	10	8		
C [3,3] [1,4]	32	30	28	26	24	22	20	18	16		
D [1,4] [2,2]										**21.27**	**16**

Notes. The entries in the upper portion of the table give the number of cooperator and defectors classed by the number of defecting neighbors. For instance, of the 87 cooperators in the final configuration, 50 had no defecting neighbors; 14 had one defecting neighbor; 12 had two defecting neighbors; and 10 had three defecting neighbors. Similarly, of the 34 defectors in the final configuration, one had three defecting neighbors; 11 had four defecting neighbors; two had five defecting neighbors; two had six had two defecting neighbors and 13 had eight defecting neighbors. The middle portion of the table gives expected payoffs in the static neighborhood subgames and the corresponding universal defection payoff D'. The expected MPG payoffs were calculated using the weighted average formula discussed in the notes of Table 3.2.

Experiment-2: The next simulation randomly adds six *Wiseguy* (W) players. Recall, the *Wiseguy's* strategy is to *always* defect no matter what strategy its eight neighbors choose. Figure 3.5 and Figure 3.6 show the initial and final configurations for this experiment. The number of cooperators in the final configuration falls to 82 from 87 in Experiment 1, while the number of defectors falls to 33 from 36 in Experiment 1.

Figure 3.5 Experiment-2: Initial Configuration with *Wiseguy* (W) Added

D	C	C	D	C	D	D	W	D	D	C
C	D	W	C	C	C	C	D	D	C	D
C	C	C	C	D	C	C	C	C	D	C
C	D	C	C	D	W	D	C	D	C	D
C	C	D	D	C	D	D	D	C	C	C
D	D	C	D	C	C	D	C	C	D	C
C	C	D	W	C	C	C	D	C	C	D
D	D	C	D	D	D	C	C	C	D	C
C	C	C	C	C	D	C	D	C	C	C
C	C	D	C	C	D	W	C	C	C	D
D	C	W	C	D	C	C	D	C	D	C

Figure 3.6 Experiment-2: Final Configuration with *Wiseguys* (W) Added

C	C	C	C	C	C	W	C	C	C	C
C	C	W	C	C	C	C	C	C	C	C
C	C	C	D	D	D	D	C	C	C	C
C	C	D	D	D	W	D	D	C	C	C
C	D	D	D	D	D	D	D	D	C	D
C	D	D	D	D	D	D	D	C	C	D
C	C	D	W	D	D	D	C	C	C	C
C	C	C	D	D	D	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	W	C	C	C	C
C	C	W	C	C	C	C	C	C	C	C

Experiment-3: This experiment randomly adds six *Goodguys*. Goodguys are agents who always cooperate (or remain unarmed) regardless of the strategies of their eight bordering neighbors. Figure 3.7 and Figure 3.8 show the initial and final configurations for this experiment respectively. In contrast to the prior experiment, the introduction of *Goodguys* has an appreciable impact on the final configuration. In the final state, the number of cooperators increases to 100 from 87 in Experiment 1, while the number of defectors drops to 15 from 36 in Experiment 1.

Figure 3.7 Experiment-3: Initial Configuration with *Goodguys* (G) Added

D	D	C	C	C	D	C	D	C	C	C
C	C	C	C	D	C	C	D	C	D	C
C	C	C	D	D	C	D	C	C	C	D
D	C	C	D	C	D	C	C	C	C	D
D	G	C	C	D	C	C	G	D	D	G
C	C	D	D	C	D	C	C	D	D	C
D	C	D	C	D	D	C	C	D	D	C
D	C	D	C	C	C	C	D	C	G	C
C	C	C	C	D	D	G	C	D	C	C
C	C	C	C	D	C	D	D	D	D	C
C	D	D	C	D	G	D	D	C	D	C

Figure 3.8 Experiment-3: Final Configuration with *Goodguys* (G) Added

C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	D	D	C	C	C	C	C
C	C	C	D	D	D	C	C	C	C	C
C	G	D	D	D	D	C	G	C	C	G
C	C	D	D	D	D	C	C	C	C	C
C	C	C	D	D	C	C	C	C	C	C
G	C	C	C	C	C	C	C	C	G	C
C	C	C	C	C	C	G	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C

Experiment-4: Figure 3.9 and Figure 3.10 show the respective initial and final configuration when two *Goodguys* and two *Wiseguys* are simultaneous included in the initial configuration. The final configuration resembles Experiment-3 with 99 cooperators and 19 defectors.

Figure 3.9 Experiment-4: Initial Configuration with *Wiseguys* (W) and *Goodguys* (G) Added

D	D	C	D	C	C	D	D	D	C	D
C	C	C	C	C	C	C	C	C	C	C
C	C	D	C	D	D	D	D	D	C	D
D	C	C	D	C	D	**W**	D	**G**	C	C
C	C	D	D	C	C	C	D	D	D	D
D	C	C	D	C	C	C	C	D	C	D
D	C	C	C	D	D	D	**W**	C	C	C
D	D	C	D	C	**G**	C	C	C	C	C
C	C	D	C	C	C	C	D	C	C	C
C	C	C	D	D	C	C	D	D	C	D
C	D	D	D	C	D	D	C	C	D	C

Figure 3.10 Experiment-4: Final Configuration with *Wiseguys* (W) and *Goodguys* (G) Added

C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	**D**	**D**	**D**	**D**	C	C	C
C	C	C	**D**	**D**	**D**	**W**	**D**	**G**	C	C
C	C	C	**D**	**D**	**D**	**D**	**D**	**D**	C	C
C	C	C	C	**D**	**D**	**D**	**D**	**D**	C	C
C	C	C	C	C	C	C	**W**	C	C	C
C	C	C	C	C	**G**	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C

Tables 3.5, 3.6, and 3.7 summarize the expected player payoffs from the above experiments. Table 3.5 shows the MPG strategy supports an equilibrium superior to universal defection. While this result is somewhat expected for Chicken, it is gratifying to see that the *Wiseguy* payoffs are much less than the *Goodguy* expected payoffs. This makes intuitive sense: always defecting in Chicken is disastrous while always cooperating with yields a relatively higher expected payoff.

Table 3.6 shows that *Wiseguys* and *Goodguys* payoffs do exceed the payoff to the MPG strategy when MSSM is the subgame payoff. Accordingly, Experiments-2 and -3 fail to meet Condition 2a (✕). This, however, does not invalidate the SSM expected payoff structure as a representation of missile proliferation. The SSM results suggest that *Wiseguy* and *Goodguy* strategies are 'saboteur' strategies that are better than the MPG strategy for the individual player but undermine equilibrium. Surpassingly, MPG supports an equilibrium superior to universal defection when *Wiseguys* and *Goodguys* are included together (Experiment-4).

The results of the MPG strategy for the MPD (see Table 3.7) meet the three Conditions for an equilibrium superior to universal defection. The policy implications of these results are addressed in the conclusion of this chapter.

Table 3.5

Chicken Payoffs for Multi-Player Game (MPG), *Wiseguys* and *Goodguys*

Experiment	**Game-Type**	**P*' MPG**	*Wiseguy*	*Goodguy*	**Final Configuration**
1.	**MPG**	18.69			Cooperators=87
					Defectors=36
					Total =121
					Cooperators=82
2.	**MPG**	21.25			Defectors=33
	Wiseguys		8.75		Wiseguys=6
					Total =121
					Cooperators=100
3.	**MPG**	20.85			Defectors=15
	Goodguy			19.00	Goodguys=6
					Total =121
					Cooperators=98
4.	**MPG**	20.24			Defectors=19
	Wiseguy		15.50		Wiseguys=2
	Goodguy			18.50	Goodguys=2
					Total =121

Notes. The MPG players are following rules (1), (2), and (3) on p. 50; the *Wiseguys* always defect and the *Goodguys* always cooperate.

Condition 1: *Global payoff incentive.* The payoff P*' to P* must exceed D'

$$P^{*\prime} > D'$$

√ **Experiment 1**: $18.69 > 8$

Condition 2a: ***Local defection disincentive.***

$$(D_k \mid P_j = P^*)' \leq ((P_k)^* \mid P^*))'$$

√ **Experiment 2**: $8.75 < 21.25$

√ **Experiment 3**: $19.00 < 20.85$

√ **Experiment 4**: $15.50 < 20.24$ and $18.50 < 20.24$

Condition 2b: ***Local defection disincentive.***

$$(P^* \mid D_k)' > D'$$

√ **Experiment 2**: $21.25 > 8.00$

√ **Experiment 3**: $20.85 > 8.00$

√ **Experiment 4**: $20.24 > 8.00$

Table 3.6

SSM Payoffs for Multi-Player Games (MPG), *Wiseguys* and *Goodguys*

Experiment	**Game-Type**	**P*' MPG**	*Wiseguy*	*Goodguy*	**Final Configuration**
1.	**MPG**	13.13			Cooperators=87 Defectors=36 Total =121
2.	**MPG** *Wiseguys*	13.59	15.00		Cooperators=82 Defectors=33 Wiseguys=6 Total =121
3.	**MPG** *Goodguy*	14.68		15.88	Cooperators=100 Defectors=15 Goodguys=6 Total =121
4.	**MPG** *Wiseguy* *Goodguy*	14.28	10.5	12.00	Cooperators=98 Defectors=19 Wiseguys=2 Goodguys=2 Total =121

Notes. The MPG players are following rules (1), (2), and (3) on p. 50; the *Wiseguys* always defect and the *Goodguys* always cooperate. The expected payoffs are calculated according to the Notes on Table 3.4.

Condition 1: *Global payoff incentive.* The payoff P*' to P* must exceed D'

$P^{*\prime} > D'$

√ Experiment 1: $13.13 > 8$

Condition 2a: *Local defection disincentive.*

$(D_k \mid P_j = P^*)' \leq ((P_k)^* \mid P^*))'$

✕ Experiment 2: $15.00 > 13.59$

✕ Experiment 3: $15.88 > 14.68$

√ Experiment 4: $10.50 < 14.28$ and $12.00 < 14.28$

Condition 2b: *Local defection disincentive.*

$(P^* \mid D_k)' > D'$

√ Experiment 2: $13.59 > 8$

√ Experiment 3: $14.68 > 8$

√ Experiment 4: $14.28 > 8$

Table 3.7

MPD Payoffs for Multi-Player Games (MPG), *Wiseguys* and *Goodguys*

Experiment	**Game-Type**	**P*' MPG**	*Wiseguy*	*Goodguy*	**Final Configuration**
1.	**MPG**	21.27			Cooperators=87
					Defectors=36
					Total =121
					Cooperators=82
2.	**MPG**	20.83			Defectors=33
	Wiseguys		16.50		Wiseguys=6
					Total =121
					Cooperators=100
3.	**MPG**	21.74			Defectors=15
	Goodguy			19.00	Goodguys=6
					Total =121
					Cooperators=98
4.	**MPG**	21.85			Defectors=19
	Wiseguy		21.00		Wiseguys=2
	Goodguy			20.00	Goodguys=2
					Total =121

Notes. The MPG players are following rules (1), (2), and (3) on p. 50; the *Wiseguys* always defect and the *Goodguys* always cooperate. The expected payoffs are calculated according to the Notes on Table 3.4

Condition 1: *Global payoff incentive.* The payoff $P^{*\prime}$ to P^* must exceed D'

$P^{*\prime} > D'$

√ Experiment 1: $21.27 > 16$

Condition 2a: ***Local defection disincentive.***

$(D_k \mid P_j = P^*)' \le ((P_k)^* \mid P^*))'$

√ Experiment 2: $16.50 < 20.83$

√ Experiment 3: $19.00 < 21.77$

√ Experiment 4: $21.20 < 21.85$ and $20.00 < 21.85$

Condition 2b: ***Local defection disincentive.***

$(P^* \mid D_k)' > D'$

√ Experiment 2: $20.83 > 16.00$

√ Experiment 3: $21.77 > 16.00$

√ Experiment 4: $21.85 > 16.00$

Conclusions

Important policy implications for arms control can be drawn from these simulations. The *Goodguy* strategy might apply to certain MTCR member countries or countries such as Lebanon who are unlikely to arm with ballistic missile regardless of how many missile threats they face. *Goodguys* might also be countries who are barred from ballistic missile technology because of the imposition of an international arms embargo. While the number of *Goodguy*s sharply reduced the number of defectors in the final configuration, always cooperating is not the 'best' strategy to play in the case of Multi-Player Chicken or Multi-Player Prisoners' Dilemma. *Goodguys* like Lebanon would probably be better off responding to missile threats in accordance to the MPG strategy. Arms embargoes or alliances that prevent countries from responding to missile threats are also an inferior strategies that can lead to systemic instability. These result challenge the conventional wisdom of arms embargoes without implementing some offsetting action to compensate the affected state for its national security losses.

Of the three subgames considered, the Multi-Player SSM (MSSM) emerges as the game theoretic structure most representative of ballistic missile proliferation because it gives a plausible explanation for the existence of *Wiseguys* and *Goodguys* in the real world. These two strategies yield expected payoffs that are higher than the D' or MPG' in Multi-Player SSM. While neither of these strategies can sustain an equilibrium, it is rational for states to play either of these two strategies because the expected payoffs exceed MPG'.

The important finding of this chapter is the experimental evidence that shows the expected MPG payoffs are better than the universal defection expected payoffs. (Recall, MPG strategy, is an extrapolation from the empirical analysis of Chapter 5). The MPG strategy also supports an equilibrium strategies superior to the invading *Wiseguy* or *Goodguy* strategies, regardless of the game-theoretic expected payoffs considered. In short, states can expect better payoffs if they respond to missile threats in accordance to the MPG strategy.

CHAPTER 4

Ballistic Missile Proliferation and the Emergence of Spatial Order

There appears to be a tendency among nations with short-ranged surface-to-surface ballistic missiles to be geographically grouped together. Geography obviously plays an important role in ballistic missile proliferation, but the game theoretic models of Chapters 2 and 3 do not make any explicit statements about the physical arrangement of players.[1] The ability to deter an opponent with ballistic missiles depends on the missile having the capability to strike desired target (s). Spatial dependency of ballistic missile proliferation was implicit in the cellular automata analysis of Chapter 3: a site's status (cooperate or defect) depended upon the number of cooperating and defecting neighbors. Despite an initial random allocation armed and unarmed sites, the 120 cells ultimately organize into clusters of defectors and cooperators. The emergence of macro-level spatial order was not the collective intention of agents or exogenously directed by a social planner; it spontaneously and solely emerged from micro-level interactions. States armed in order to maximize their expected payoffs from a subgame with its eight nearest neighbors. An unintended spatial order emerged from strategic interactions of players.

The notion that systems in which randomness and chaos seem to spontaneously emerge into an unexpected order is not new. A familiar example of the emergent property of self-organization was stated more than 200 years ago when Adam Smith wrote the way that markets lead participants, " as if by an invisible hand," to outcomes no one intended. Individually, each person is primarily concerned with their maximizing his or her own consumer or producer surplus and in doing so create and emergent property known as a market.[2] Emergence has been identified in natural phenomenon like earthquakes (Bak and Tang, 1989), neural networks of the human brain (Hopfield, 1982) and urban segregation (Schelling, 1978). This chapter examines the empirical emergence of spatial order in ballistic missile proliferation.

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[1] Indeed, ballistic missiles are concentrated in the Middle East, North Africa, and Asia.

Spatial Autocorrelation

It is often necessary to consider the spatial distribution of some phenomenon to better understand and predict its occurrence.[3] If there is systematic spatial variation, then the phenomenon being studied is said to exhibit *spatial autocorrelation* (Cliff and Ord, 1981). *Spatial autocorrelation* exists when the value of a variable at a given location depends on the value of the variable at contiguous locations (Black, 1992). Spatial autocorrelation means neighbors have influences on each other in geographic space. Neighbors are defined to share a non-zero length of boundary.

Neighbors can have varying degrees of influence on one another. As we have seen with the *Goodguys* and *Wiseguys* of the previous chapter, neighborhood influences need not always be symmetrical or complementary. *Positive* spatial autocorrelation indicates that similar values for the variable in question are clustered together in space (e.g. concentration of manufacturing firms in industrial areas). *Negative* spatial autocorrelation indicates that similar values are separated by intervening dissimilar values. That is, dissimilar values are clustered in space. Alternatively, *random* autocorrelation indicates that the event is random across space (Vasiliev, 1996, p. 24).

Figure 4.1 depicts an example of *positive* spatial autocorrelation; like values tend to be adjacent to one another. An analogous comment can be made about Figure 4.2 except that the tendency is for dissimilar values to be adjacent to one another; giving rise to *negative* spatial autocorrelation. Finally, Figure 4.3 shows a random spatial allocation of cooperators and defectors with no apparent spatial dependency.

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[2] When participants of an experimental markets are assigned payoffs and then make bids for and offers of a units of notional commodity, the come very close to maximizing aggregate surplus even though they are unaware of trying to achieve this objective (Krugman, 1995, p. 3).

to *negative* spatial autocorrelation. Finally, Figure 4.3 shows a random spatial allocation of cooperators and defectors with no apparent spatial dependency.

Figure 4.1 Positive Autocorrelation

D	*D*	*D*	*D*	C	C	C	C
D	*D*	*D*	*D*	C	C	C	C
D	*D*	*D*	*D*	C	C	C	C
D	*D*	*D*	*D*	C	C	C	C
D	*D*	*D*	*D*	C	C	C	C
D	*D*	*D*	*D*	C	C	C	C
D	*D*	*D*	*D*	C	C	C	C
D	*D*	*D*	*D*	C	C	C	C

Note. Like cells are clustered

Figure 4.2 Negative Autocorrelation

D	C	*D*	C	*D*	C	*D*	C
C	*D*	C	*D*	C	*D*	C	*D*
D	C	*D*	C	*D*	C	*D*	C
C	*D*	C	*D*	C	*D*	C	*D*
D	C	*D*	C	*D*	C	*D*	C
C	*D*	C	*D*	C	*D*	C	*D*
D	C	*D*	C	*D*	C	*D*	C
C	*D*	C	*D*	C	*D*	C	*D*

Notes. Like cells are separated

Figure 4.3 Random Autocorrelation

C	C	*D*	C	C	C	C	*D*
C	*D*	*D*	*D*	C	*D*	C	C
C	C	*D*	*D*	C	*D*	*D*	C
C	*D*	*D*	C	*D*	C	C	C
D	C	*D*	*D*	*D*	C	C	*D*
D	C	*D*	*D*	*D*	C	*D*	*D*
D	C	*D*	C	C	*D*	*D*	C
C	C	C	*D*	*D*	C	*D*	*D*

Notes. No particular pattern

Join Count Statistic

A binary classification called the *join count statistic* is often used in examining spatial autocorrelation for nominal scale variables (Unwin, 1981). The variable X_i in country *i* is defined to as:

$$X_i = \begin{cases} \mathbf{1, \text{ if the } \mathit{i} \text{ th cell is D}} \\ \mathbf{0, \text{ if the } \mathit{i} \text{ th cell is C}} \end{cases} \qquad \mathbf{(4.1)}$$

If a country defects the country is coded D; if it cooperates it is coded C. If two countries share a common boundary they are said to be linked by a join. A join may connect two cooperating countries; two defecting countries; a cooperating country to a defecting country (and visa versa). These borders are designed CC joins, DD joins, and DC joins respectively.

The join counts for Figures 4.1, 4.2 and 4.3 are included in Figures 4.4, 4.5, and 4.6. Notice that the joins counted exclude those that touch the corners. This representation is called the 'rook's case' and corresponds to the cellular automata's von Neumann neighborhood.[4]

Intuitively, the join count acts as indicators of spatial autocorrelation. The spatial clustering of similar cells (e.g. defectors with defectors and cooperators with cooperators) implies a relatively high number of DD and CC joins and relatively few DC. Conversely, the clustering of dissimilar cells (e.g. defectors with cooperators) implies a relatively high number of DC joins and relatively few DD and/ or CC joins. A random allocation would approximate the number of DC joins to be roughly equivalent to the sum of DD and CC joins.

Figures 4.4, 4.5, and 4.6 show the join counts for Figures 4.1, 4.2, and 4.3 respectively. The number of DD and CC joins are much greater than the DC joins (52 versus 8) in the case of positive spatial autocorrelation. For negative spatial autocorrelation, the number of DD and CC is less than the number of DC joins (60 versus 21). Figure 4.6 shows the random case with the number DC equal to the sum of DD and CC joins.

The critical step in the logic in spatial analysis is to view these figures as the result of a processes. The 'order from disorder' phenomenon observed in the previous chapter's simulations, depicted ballistic missile proliferation as starting from a random configuration like Figures 4.3 and 4.5 and ending up as positive spatial autocorrelation like Figures 4.1 and 4.4. The observed pattern of join types over time, can give us insights on the emergence of spatial order in the process of ballistic missile proliferation.

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[4] The eight-neighborhood case, which corresponds to the Moore neighborhood, is called the Queen's case and is not shown here.

Figure 4.4 **Positive Spatial Autocorrelation**

D	D	D	D	C	C	C	C
D	D	D	D	C	C	C	C
D	D	D	D	C	C	C	C
D	D	D	D	C	C	C	C
D	D	D	D	C	C	C	C
D	D	D	D	C	C	C	C
D	D	D	D	C	C	C	C
D	D	D	D	C	C	C	C

Join Count:
CC = 52
DD = 52
CD = 8

Figure 4.5 **Negative Autocorrelation**

D	C	D	C	D	C	D	C
C	D	C	D	C	D	C	D
D	C	D	C	D	C	D	C
C	D	C	D	C	D	C	D
D	C	D	C	D	C	D	C
C	D	C	D	C	D	C	D
D	C	D	C	D	C	D	C
C	D	C	D	C	D	C	D

Join Count:
CC = 21
DD = 21
DC = 60

Figure 4.6 **Random Spatial Autocorrelation**

C	C	D	C	C	C	C	D
C	D	D	D	C	D	C	C
C	C	D	D	C	D	D	C
C	D	D	C	D	C	C	C
D	C	D	D	D	C	C	D
D	C	D	D	D	C	D	D
D	C	D	C	C	D	D	C
C	C	C	D	D	C	D	D

Join Count:
CC = 25
DD = 27
DC = 50

Illustrative Example

As an example, consider the join-count for nation of Egypt. Egypt borders five nations: Israel, Jordan, Libya, Sudan and Saudi Arabia. In 1975 Israel had *Jericho–I* ballistic missiles and Egypt had *Scud B* ballistic missiles. In 1975 Egypt shared a borders with *one* country that had ballistic missiles-Israel, and *four* countries that did not: Libya Saudi Arabia, Jordan, and Sudan.

Table 4.1

Join Count for Egypt in 1975

Join Type	Join Count	Comment
CC	0	Egypt has missile; none of its joins can be CC
DD	1	Egypt-Israel border
DC	4	Egypt-Sudan , Egypt-Libyan, Egypt-Jordan, and Egypt-Saudi Arabia
Sum	5	Total number of joins = total number of borders

Libya acquired *Scud B* missiles in 1978. This changed the distribution of join counts for Libya's neighboring states: Algeria, Tunisia, Sudan, Chad, and Egypt. Table 4.2 summarizes the changes to Egypt's join count resulted from Libya's *Scud B* acquisition.

Table 4.2

Join Count for Egypt in 1980

Join Type	Join Count	Comment
CC	0	Egypt has missiles; none of its joins can be CC
DD	2	Egypt-Israel, Egypt-Libyan
DC	3	Egypt-Sudan, Egypt-Jordan, Egypt-Saudi Arabia
Sum	5	Total number of joins = total number of borders

Cliff and Ord (1981) derive the following formal equations for the join count.

$$\mathbf{CC = \Sigma\Sigma\delta_{ij}\, x_i\, x_j} \qquad (4.2)$$

$$\mathbf{DC = \Sigma\Sigma\delta_{ij}\,(x_i - x_j)^2} \qquad (4.3)$$

$$\mathbf{DD = \Sigma\Sigma\, \delta_{ij}\,(1 - x_i)(1 - x_j)} \qquad (4.4)$$

Where δ is a connection matrix in which $\delta_{ij} = 1$ if the *i*th and *j*th countries are joined and $\delta_{ij} = 0$ otherwise. Table 4.3 applies equations (1), (2), and (3) to a sample of 119 in 1967, 1977, 1987 and 139 countries in 1997.

Table 4.3

Join Count for Selected Years

	1967		1977		1987		1997	
	Join Count	%	Joins Count	%	Joins Count	%	Joins Count	%
CC	340	71.72	276	58.22	243	51.12	285	54.49
DD	20	4.21	72	15.18	81	17.08	90	17.20
DC	114	24.05	126	26.58	128	27.00	148	28.29
Total	474	100.00	474	100.00	474	100.00	523	100.00

Notes. For a complete list of countries included see Table A2, Appendix B.

Table 4.3 show that as ballistic missiles spread, the CC joins declined by roughly 17% and the DD joins increased more than four fold in absolute terms. The DC joins remain relatively constant over the forty-year period. Thus the increase in DD joins appears to be related to the decrease on CC joins.

In each of the four time periods DC << CC + DD suggesting the that missile proliferation is spatially dependent. We can arrive at a more precise representation of this spatial dependency through the *join count statistic*. Work presented in Unwin (1981, p. 140-141) shows the first two moments (location and scale of normal) under the assumption of free sampling to be:

$$\textbf{expected number of CC joins} = kp^2 \qquad (4.5)$$

$$\textbf{expected number of DD joins} = kq^2 \qquad (4.6)$$

$$\textbf{expected number of DC joins} = 2kpq \qquad (4.7)$$

$$\textbf{standard deviation CC} = [kp^2 + 2mp^3 (k + 2m)p^2]^{0.5} \qquad (4.8)$$

$$\textbf{standard deviation DD} = [kp^2 + 2mq^3 (k + 2m)q^2]^{0.5} \qquad (4.9)$$

$$\textbf{standard deviation DC} = [2 (k + m)pq - 4(k + 2m)q^2p^2]^{0.5} \qquad (4.10)$$

m is defined as:

$$m = 0.5 \Sigma j_i (j_i - 1) \qquad (4.11)$$

where *k* is the total number of joins for a given map, *q* = probability of a country being D; q = the probability of a country being coded C or 1- *p*.

The probability of any one specific number of joins of a particular type given the independent random process, can be found by calculating the standard normal deviate or z-score:

$$z = \frac{\text{observed number of joins - expected number of joins}}{\text{standard deviation of expected values}} \qquad (4.12)$$

$$p = \frac{\text{the number of countries designated D in a region}}{\text{total number of countries}} \qquad (4.13)$$

$$q = 1 - p \qquad (4.14)$$

Table 4.4

Z-scores for the Join Counts

	Europe		Asia		MENA	
Join Type	1967	1990	1967	1990	1967	1990
CC	-1.03	0.72	-0.10	-0.80	0.30	0.47
DD	-0.36	2.05*	0.78	2.54*	-0.37	1.48
DC	1.10	-1.34	0.26	0.04	0.33	-2.53*

* Significant at the 5% level of confidence

Table 4.4 displays the *z-scores* for the three join parameters CC, DD, and DC for Europe, Asia and the MENA. Since no direction (positive or negative) is specified for autocorrelation, a two-tailed test is applied. Rejection of the null hypothesis requires a *z-score* greater than 1.96 in magnitude. The joins exhibits surprisingly simple regularities across regions. The *z-scores* for the initial adoption periods indicate the existence of a spatial structure for each region that is not significantly different from a random configuration. However, as ballistic missiles proliferate over several decades, a distinctive pattern of positive autocorrelation emerges.

Starting with the equivalent of a random distribution of join allocations for each region, a highly regular pattern of *positive* autocorrelation emerges in each of the three regions in 1990. The initial distribution of joins are very close to the expected values for each region under the null hypothesis. That is, the observed join count is not statistically different the joins count expected under the condition of no spatial autocorrelation. As ballistic missiles spread in each region, a remarkably consistent pattern of positive spatial autocorrelation emerges from an initially random distribution of joins.

The join count analysis suggest that procurement actions of nations are principally local or influenced by their immediate neighbors. However, the tendency of nations to arm themselves in response to the procurement decisions of their immediate neighbors starts a dynamic process that ultimately produces a highly regular form of spatial autocorrelation.

Conclusions

This chapter shows that a pattern of positive spatial autocorrelation emerges from an initially random spatial distribution of ballistic missiles in three regions: Asia, the Middle East/North African and Europe. However, because the join count is a nominal measurement, it suffers from 'topological invariance' meaning that the size and shape of the objects being studied are ignore. The size and shape of countries obviously play important roles in international relations and ballistic missile proliferation. Land area determines the *effective* range of ballistic missiles. For instance, India's *Agni II* and Pakistan's *Ghauri II* intermediate range ballistic missiles have roughly the same size and payload capabilities, yet because of size and position the Indian subcontinent, New Delhi can reach far more distant targets. The impact missile threats have on countries not bordering India but within striking distance of the *Agni II,* are ignored in the join count analysis. The next chapter develops several regression models to explain ballistic missile proliferation. This approach allows us to explain ballistic missile proliferation while controlling for size and other intervening factors.

The join means and standard deviations (Equations 4.5 – 4.1) were calculated assuming p and q are independent and are known *ex ante*. In reality, the probabilities p and q (e.g. the probability that a country will or will not procure ballistic missiles) are not generally known. I estimated these probabilities using the data: $p = n_l / n$ and $q = 1 - p$ (see Equations 4.13 and 4.14).

One common approach is to assumes an independent process and use probability theory to predict what values of the join count would be expected in the long run. Cliff and Ord (1981) show that as *n* (the number of countries) increases, the join-count statistic is asymptotically normally distributed for lattices of moderate size and can be accurately tested for significance a standard normal deviates.[5]

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[5] Cliff and Ord (1973) show that join-count statistic only has a normal distribution as *n* approaches infinity. In practical terms, the normal approximation is reasonable if: *n* is moderately large (50) and the probabilities *p* and *q* are no to near 0 and 1 and if the lattice is not dominated by one or two very large areas (Unwin, 1981, p. 140). For the countries in the three regions considered *n* is small but the normal approximation appear to be good assumption.

CHAPTER 5

Empirical Analyze of Ballistic Missile Proliferation

Fundamentally, an arms race "involves political-economic choice. The nations (groups or leaders) involved ... must decided how to allocate scarce resources to defense and non-defense subject to political constraints" Anderton (1989, p 335). In the gaming models of Chapter 2, countries had two strategies: defection (arming) or cooperating (disarming). The choice of strategy depended upon each country maximizing its security payoff vis-à-vis its opponent. In the prisoners' dilemma and SSM games, the dominant strategy was to defect, even though mutual cooperation gave both countries greater payoffs. Chapter 3 expanded the 2-player gaming models to a multiple player contests in which the MPG strategy yielded. In Chapter 4, I showed that decision to arm was spatially dependent and that missile proliferation resulted in a geographic clustering of defectors and cooperators. Chapter 6 builds upon the previous chapters by incorporating spatial correlation and game-theoretic strategies into a regression-based empirical analysis in an effort to better explain ballistic missile proliferation. In Part I, I explain the decision to defect with the number of armed neighbors. In Part II, I explain the variation in ballistic missile payloads with the number of armed neighbors.

Part I Discrete Choice Analysis

Train (1986) describes a qualitative choice situation in which a decision-maker faces a choice of set of alternative meeting the following criteria: (1) the alternatives are mutually exclusive (2) the alternatives are finite; and (3) the set of alternatives is exhaustive. The decision to procure ballistic missiles fits these criteria. The *defect* and *cooperate* strategies are clearly mutually exclusive; countries can not both cooperate and defect simultaneously. The alternatives are exhaustive since there are no weapon alternatives to countering the threat of a ballistic missile. Nor does any other weapon have the assured penetration capability of the ballistic missile.[1]

All qualitative choice models calculate the probability that a decision-maker will choose a particular alternative from a set of alternatives (Train, 1986). Discrete choice models provide a way of looking at a rich set of hypotheses concerning missile proliferation. We can draw upon in specifying and interpreting econometric models to a degree that was not possible with the spatial analysis or game theory. Second, more information about countries can be included, making more precise estimation of the underlying dynamics of missile proliferation. Qualitative response analysis allows us to examine ballistic missile proliferation in spatial and temporal context simultaneously. Moreover, a regression-based analysis permits the inclusion of factors such factors as

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[1] Most cruise missiles produced since the Nazi *V-1* are good for attacking ships and airplanes or for defending coastal areas. Over 70 countries (40 of them in the developing world) possess more than 75,000 anti-ship cruise missiles, most with ranges under 100km. However, for the time period considered, only the United States and Russia deploy long-range land-attack sea launched cruise missiles: the U.S. has the *Tomamhawk* and Russia has the *SS-N-21 Sampson*, sometimes referred to as "*Tomakawski*". The type of anti-ship cruise missiles in most regional arsenals can not be used effectively for land attack missions because their guidance systems cannot distinguish targets on land from their background (Mack, 1991).This is primarily because strict export controls have effectively prevented the spread of highly accurate guidance schemes like Terrain Contour Matching (TERCOM) systems or Digital Scene-Matching Area Correlator (DSMAC) systems. Andrew Mack (1991, p.46) predicts that the TERCOM guidance systems used on the *Tomahawk* cruise missiles "will not be emulated in by Third World State for along time, if ever."

country size, shape, and spatial statistics as well as institutional factors such as norms. Finally, the discrete choice framework allows us to retain the theoretical game theoretic framework of defection and cooperation.

The Model

In Chapter 3, I derived a pure-strategy Nash equilibrium for the number of missiles as a function of the number of armed neighbors.

$$\mathbf{m}^*_1 = \mathbf{m}^*_2 = (1 + f(J)\,\mathbf{b}) / (2\mathbf{b} - \mathbf{d}) \qquad (5.1)$$

Where $\mathbf{m}^*_1$ is the number of missiles and J is the number of armed neighbors. The counter missile threats from J countries is embodied in the term $f(J)$, which is a function that increases as J increases.

Unfortunately, a consistent measurement of the exact number of missiles in national arsenals is unavailable for many countries. However, deployment and testing dates are annually recorded in *The Military Balance* (International Institute for Strategic Studies, London).[2] So instead of explaining the number of missiles as equation (5.1) suggest, I will predict the probability that country defects given that it has **J** armed neighbors.

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[2] Ideally, annual Y would equal the number missiles in each country per time period. Unlike the strategic ballistic missile arsenals of the superpowers during the cold war in which exact numbers were known, little is known about the exact size of missile arsenals in other countries, particularly in regional rocket programs. The only characteristics consistently reported are the approximate age of the program, range and payload. Countries are generally unwilling to reveal specifics on their arsenals. Consequently, it becomes extremely difficult to reach unanimous conclusions about the number of missiles deployed, payloads, accuracies, and ranges. Navias (1993) reports that the state of missile forces are closely guarded secrets. The reason for this include: protection of national security; ballistic missiles projects are linked together other highly secretive projects such as nuclear and chemical weapons development. Secretiveness also

The dependent variable, Y takes only two values 0 and 1:

$$Y_{it} = \begin{cases} 1; & \text{if a country } i \text{ possessed ballistic missiles at time } t. \\ 0; & \text{otherwise.} \end{cases} \qquad (5.2)$$

Conventional ordinary least squares (OLS) regression methods are inappropriate here, since there is no guarantee that the predicted values will lie between zero and one (Greene 1993). Further, we assume that the probability of defection, Prob (Y = 1), depends on a vector of independent variables, **X** and a vector of unknown parameters **β**. Using the subscript *i* to denote the *i*th country, we can write a dichotomous model of ballistic missile proliferation as:

$$\mathbf{Prob}\ (\mathbf{Y}_{it} = \mathbf{1}) = F(\mathbf{X}_{it}\,\boldsymbol{\beta}) \qquad (5.3)$$

$$i = 1, 2, \ldots n; \; t = 1967, 1968 \ldots 1997$$

Equation 5.3 states that the probability that the *i*th country has ballistic missiles at time *t* depends on the vector $\mathbf{X}_{it}$ representing the characteristics of the *i*th country at time *t*. In other words, the probability that a country has ballistic missiles depends on a linear combination of observed variables $\mathbf{X}_i$ with weights given by the coefficients β. An estimated β value does not estimate the change in the probability of Y =1 due to a unit change in the relevant explanatory variables. In order to constrain the model's predictions to the [0, 1] interval, we employ either a logic or probit model. Other distributions have been suggested, in econometric applications the probit and logit models have been used almost exclusively (Greene, 1993, p. 637). The sign and significance (t-statistic) of the probit and logit coefficient have the interpretations comparable to the OLS regression coefficients. For purposes of explaining ballistic missile proliferation, the coefficient's

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reinforces the prestige and deterrent attributes of these weapons systems.

sign and significance should provide sufficient evidence of spatial autocorrelation: positive values of β imply that increasing values of **X** increase the probability that a country has ballistic missiles; negative values imply the opposite. The structural model for a panel of data can be written as:

$$\mathbf{Y}^*_{it} = \mathbf{X}_{it}\beta + \varepsilon_{it} \qquad \varepsilon_{it} \sim \mathbf{N}[0,1] \qquad (5.4)$$

where $t = 1, 2, \ldots$ T and the index of observations within cluster $i = 1, 2, \ldots N$ and $\mathbf{X}_{it}$ is a 1 x k vector of explanatory variables and β is a k x 1 vector of coefficients.[3] The probit specification is given by

$$\mathbf{Prob}\ (\mathbf{Y}^*_{it} = 1 \mid \mathbf{X}_{it}) = \Phi\ (\beta \mathbf{x}_{it}) \qquad (5.5)$$

Where Φ is the standard normal cumulative distribution function. Alternatively, the logistic distribution is popular in many qualitative choice models, partly because of its mathematical convenience,

$$\mathbf{Prob}(\mathbf{Y} = 1) = \frac{\mathbf{Exp}(\mathbf{X}_{i,t}\beta)}{1 + \mathbf{Exp}(\mathbf{X}_{i,t}\beta)} \qquad (5.6)$$

Table 5.1 summarizes the explanatory variables included in $\mathbf{X}_{it}$. Except when noted, the variables are for the 1967 to 1997 time period. This era was chosen because avoids the complications associated with it colonial borders.[4] I have divided the explanatory variables into three broad categories: Strategic, Spatial, and Institutional to

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[3] The unobserved variable $\mathbf{Y}_{it} = 1$ if $\mathbf{Y}^*_{it} > 0$ and is zero otherwise.

[4] This era also offers the opportunity to compare the model before and after the collapse of the Soviet Union. The end of the cold war brought not only about the end of Warsaw Pact alliance it fundamentally changed the border and hence interactions among the states of Eastern Europe and Central Asia. The huge Soviet missile arsenal was eventually divide among Khazakstan, Uzbekistan, the Ukraine, Turkmenistan, and Russia.

facilitate their interpretation. The following section, elaborates on the theoretical justification for including these variables in the model.

Table 5.1

List of Explanatory Variables

	Description
Strategic Variables:	
J_k	Equals one if a country has *k* neighbors with missiles and is zero otherwise. $k = 1, 2, 3, 4$ and more.
S_m	Equals one if a country faces *m* missile threats and zero otherwise. $m = 1, 2, 3, 4, 5, 6, 7, 8$ and more.
NSAM	Number of neighboring states with surface-to-air missiles (SAMs)
SAM	Equals one if country *i* had SAMs, zero otherwise.
Spatial Variables:	
Borders	Number of international borders
DC	The number of *DC* joins
DC^2	The number of *DC* joins squared
Area	The log of the nation's area in square kilometers
Institutional Variables:	
Norms	Sum of the GNPs of MTCR members over GNP of the world
NATO	Equals one if the country was a NATO member, zero otherwise
WTO	Equals on if the country was a Warsaw Pact member, zero otherwise
Milex	Military expenditures as a percent of central government expenditures, ME/ CGE.

Notes. All variables refer to the 1967-1997 time period. Data sources listed in Appendix B.

Strategic Variables

This model test the hypothesis that the chance an individual country procures ballistic missiles increases as the number of neighbors with ballistic missiles increases. As a country's neighbors arm, the number of missile threats it faces increases. Should an unarmed country choose to ignore these threats, it runs the risk of exploitation. What we want to determine is how many armed neighbor must a country have before it defects. The sign and significance of the $\mathbf{J_k}$ coefficients will reveal the threshold condition that trigger a nation to arm.

Since an intercept is to be included in the specification, four $\mathbf{J_k}$ dummies, $k = 1, 2, 3, 4$ and more are considered. Including J_k dummy variables for each category (e.g. $k = 1, 2, 3\ldots n$) runs the risk of perfect multicollinarity because the intercept, β_0 is represented as column of 1s. In other words, the sum of J_k is a *linear combination* of the intercept, which violates a critical assumption underlying classical regression model. With perfect multicollinarity it is impossible to separate out the individual effects of the component of J_k and the regression will not run. Econometrically, this is known as the 'dummy variable trap'; forgetting to omit the dummy variable for one category when an intercept is included, since if a dummy is included for all categories an exact linear relationship will exist between the dummies and the intercept (Kennedy, 1992). The omitted category picked-up by the intercept is the case of countries with no neighbors with ballistic missiles.

Some ballistic missiles have ranges that allow countries to target more than their immediate neighbors. The immediate neighbor category J_k is too restrictive in this sense. Accordingly, I include $\mathbf{S_m}$ to measure the interaction of contiguous and non-contiguous neighboring missiles. The $\mathbf{S}_m$ dummy variables will include all of the countries J_k bordering missiles variables threats as well as non contiguous missile threats. In other words, the J_k dummies are a subset of the $\mathbf{S}_m$ dummies. For instance, S_1 includes all countries threatened by with one ballistic missiles, regardless of political geography. Because of the obvious potential for multicollinarity, these two sets of dummy variables, are entered into the regression equation separately. Although there is considerable overlap between $\mathbf{S}_m$ and $\mathbf{J}_k$ there is an important qualitative difference between these two variables. The $\mathbf{S}_m$ dummies ignore the geographic proximity of the threat while the J_k dummies are tied to geography by virtue of their definition. I the model with $\mathbf{S}_m$ dummies the *Nonspecific Missile Threat Model* and the model with $\mathbf{J}_k$ dummies the *Specific Missile Threat Model.*

Spatial Variables

The number of international borders, **Borders** is included to control for the effect of contiguity might have on procurement decisions. The evidence linking conflict with geographic proximity is scattered but generally consistent (Bremer, 1992). In a study of conflict in Africa from 1960 - 1977, Most and Starr (1983, p. 113) found that "[M]ore borders are related to more conflict and that conflict has the tendency to diffuse spatially along the lines of… inter state borders." The border/ conflict hypothesis is a concept robust enough to handle global or regional samples, different time periods and different interpretations of war (Starr and Most, 1983, p.113). Eyre and Suchman (1996, p. 103) use "the number of borders as a rough indicator of the potential for friction" between countries. In his analysis of 33 nation-states, Richardson (1960, p. 176) found "a correlation [r = + .77] between the number of frontiers and the number of external wars. Bremer (1992) convincingly established the 'presence of contiguity' as a leading factor in interstate conflict.

Size (land area) makes a country vulnerable to non contiguous missile threats. Everything else being equal, a larger country is more vulnerable to missiles strikes neighbors than a smaller country. For instance, in 1990, Saudi Arabia was vulnerable to missile from ten countries: Egypt, India, Israel, Iran, Iraq, Syria, Yemen, USSR, France, West Germany; whereas neighboring Jordan was vulnerable to missiles from Egypt, Iraq, Israel, Syria, USSR, France, West Germany. **Area** controls for the impact non contiguous missiles threats have on ballistic missile procurement decisions.

Preliminary data analysis of my sample of 3733 observations, shows that defecting countries have more *DC* joins than cooperating countries. Recall, that the DC variable combines both the *DC* joins and *CD* joins. Table 5.2 displays the break-down of DC in to its composite join categories for the defect (Y=1) and cooperate (Y=0) strategy.

Table 5.2

Average *DC*, *CD* and DC Join Counts (N=3733)

Strategy	Join Type	Average Number of Joins
Defect (Y=1)	*DC*	2.41
Cooperate (Y=0)	*CD*	0.69
Weighted Average	DC	1.09

Notes. See Appendix B for countries included

Unfortunately, the number of *DC* and *CD* join types cannot be entered into the regression equation as explanatory variables because they would perfectly predict the dependent variable. I instead add **DC** and **DC^2** to the regression, reasoning the former variable would proxy the *CD* joins and later variable would proxy the *DC* joins. Table 5.2 suggest that the coefficient of DC coefficient should be negative and the coefficient of DC^2 should be positive.

Table 5.2 is consistent with the payoffs and logic of the Prisoners' Dilemma (PD), Chicken, and SSM games of Chapter 2. In these games, cooperating with a defector (CD) leaves a state open to exploitation (2, 4-Chicken; 1, 4-PD; and 0, 2-SSM) , whereas defecting against a cooperator (DC) gives a player his highest payoff (4, 2-Chicken; 4, 1-PD and 2, 0-SSM). The empirical evidence in Table 5.2 suggest that states prefer DC strategy (defecting against cooperators) rather than the CD strategy (cooperating with defectors).

Countries are said to procure ballistic missiles because they want the ability to penetrate neighboring air defenses (Harvey, 1991; Navias, 1993). I test the validity of this hypothesis with the variable **NSAM**, the number of bordering countries with surface-to-air missiles or SAMs. Shimshoni (1990, p. 193-194) argues that military operations are composed of integrated tactical offensive and tactical defensive components-in parallel, series or both. I include a dummy variable **SAM** to test the complementarily of ballistic missiles and SAMs.[5]

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[5] A nation's air defenses are obviously consist of more than surface-to-air missiles (SAM). However, the deployment of SAMs implies a higher level of systems integration relative to countries without surface-to-

Institutional Variables

Institionalists' approach to international relations theory emphasizes the role of world-level cultural models that "press all countries toward common objectives, forms, and practices" (Eyre and Suchmann, 1996, p. 86). These observed 'objectives, forms, and practices' are often termed *norms* and are generally observed for cultural. Slavery, for instance, "was imagined as an immutable part of the natural social order. Hence, it was utopian to advocate its abolition" (Kim, 1984, p. 81). Nevertheless slavery "disappeared because international norms against it are strong" Lee (1989, p. 406-407). Kegley and Raymond (1986, p. 213) have found that norm-based regimes may have a constraining impact on the incidence of war in the global system. Karp (1996, p. 27) points out that "if ballistic missile proliferation is to arrested once and for all, it will be necessary to create a universal norm."

In 1987, seven major industrial countries initiated a suppliers cartel called the missile technology control regime (MTCR) in an effort to end the spread of ballistic missiles. MTCR is an informal agreement to prohibit the transfer of ballistic missiles and related technologies to non-member states.[6] By 1997, the regime's membership tripled to 21 partners. Over the course of the regime's history, the MTCR guidelines and Annex have become the international standard for missile related technology export behavior. The regime has been credited with slowing missile proliferation worldwide (U.S.ACDA,

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air missiles. SAM is a dummy variable that broadly categorizes air defense capabilities.

[6] The MTCR restricts the export of ballistic missiles capable of carrying a payload of 500 kilograms to a range of at least 300 kilometers, as well as key missile components and technology to non-members. It contains no monitoring authority or sanction mechanism for violators who are members. Category I of the protocol, prohibits the transfer of complete missile systems, and key components such as missile stages, and some production equipment, while Category II regulates the transfer of specific missile components and dual-use goods to produce missiles. *The Proliferation Primer: A Majority Report on the Subcommittee on International Security, Proliferation, and Federal Services.* United States Senate, Committee on Government Affairs, Washington D.C., 1998.

1997). Ozga (1994, p. 4) argues that the "MTCR provides the international norms for dealing with the diffusion of ballistic missile technology". She contends the " most-often cited rational for [MTCR] participation is a state's desire to accede to global nonproliferation norms. A nation endorsing the MTCR aligns itself with a select group and demonstrates its willingness to cooperate with in good faith with the international community." Declaring support for the regime deflects political pressure and/ or removes stanchions when a nation comes under criticism for its arms export policies. This is consistent with the institutionalist view that the "world is a cultural system, structured by an evolving set of category prescriptions and proscriptions that define and delimit appropriate action" (Eyre and Suchmann, 1996, p. 88).

Putative MTCR actions have shaped international attitudes and opinions about ballistic missiles proliferation. Between 1987 and 1996, the United States imposed export MTCR related import/export sanctions on seven different occasions against companies and/ or government agencies in China, India, Iran, North Korea, Pakistan, Russia, South Africa, and Syria.[7] According to Lora L. Lumpe (May, 1996) "The imposition of MTCR sanctions by the United States has generated a great deal of diplomatic and economic pressure as well as negative press and public opinion. Most nations are quite concerned that they not be branded as violators of this non-proliferation norm because of the associated costs."

I define **Norms** as the ratio of the sum of the GNPs of countries observing MTCR export regulations over the sum of the GNP of all countries in the sample. Since the impact that individual nations have formulating international norms is not equivalent,

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[7] In most of these cases, the charges involved short-ranged missiles, posing no direct threat to the United States (Lumpe, 1996).

Norms is weighted by GNP. This representation assumes aggregate economic output is proxy variable for influence countries have in establishing international norms. As more nations join the MTCR, **Norms** will approach one.

Possessing ballistic missiles is not just a phenomenon of a few 'rogue states' in the third world. Ballistic missiles have been an integral part of European security for decades. Ballistic missile proliferation in Europe dates back to the late 1950s with deployment of American-made *Thor* and *Jupiter* intermediate range ballistic missiles to selected North American Treaty Organization (NATO) countries: Britain, Italy, Turkey and West Germany. Soviet-made *Scud*, *SS-21*, *SS-23*, and *FROG* rockets began making their appearance in Warsaw Treaty Organization (WTO) states starting in the early 1970s. Hansen, Murdoch, and Sandler (1990, p. 41) suggest that conventional weapons among allies have become complements. "In fact, an increase in others' allies conventional expenditures should induce the non-nuclear ally to spend more on conventional armaments so the it does not appear weak." Appearing weak would presumably increase the probability of becoming the initial battleground. If some alliance member procures ballistic missiles, this allegedly drives other alliance members to procure ballistic missiles. If weapons and alliances are complementary, alliance members should acquire ballistic missiles as their allies do. Ballistic missile deployment dates for NATO and WTO members suggest complementarily (See Appendix, Table A2).[8] Empirical analysis by Murdoch and Sandler, 1982, 1984 and Hansen et. al (1990) indicates that defense expenditures for many NATO allies were positively correlated during the late 1970s and early 1980s. **NATO** and **WTO** are dummy variables included

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[8] This model contrast with earlier alliance models, which assume that defense goods alliances are substitutes. These models use Hicksian definition of substitutes and complements to cases where there are

to account for the impact NATO and Warsaw Treaty Organization (Warsaw Pact) membership had on missile proliferation

Military expenditures as percent of central government expenditures (ME/CGE), **Milex** controls for impact that wars and militarization might have on ballistic missile proliferation. The U.S. Arms Control and Disarmament Agency, which collects, estimates and publishes data on **Milex**, identifies the statistic as an 'indicator of milarization' or a measurement of military burden.[9] Generally, in times of war, military expenditures increase as a percent of central government expenditures because governments at war allocate more resources to military expenditures than countries not at war (U.S. ACDA, 1977; US ACDA, 1993).

Table 5.3 shows military expenditures as percent of central government expenditures for selected regions and dates. Military outlays consumed more than half of the central government expenditures in the Middle East during the Gulf war period. Prior to the collapse of the USSR, military expenditures in WTO countries accounted for as much as 43% of central government expenditures. In contrast military expenditures in NATO countries on average consumed at most 14.6% of central government expenditures.

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three or more goods (Samuelson, 1974).

[9] In addition to estimating total military expenditures on hardware procurement, Milex includes government expenditures on manpower, infrastructures (e.g. military bases), and research and development.

Table 5.3

The Military Expenditures as a of Central Government Expenditures (%)

	1983	1989	1991	1993
Region				
Middle East	31.2	34.2	53.1	24.9
North Africa	20.7	16.9	12.3	12.3
NATO	14.6	14.3	11.7	10.9
WTO	43.5	38.4	37.2	15.0
East Asia	13.5	11.7	11.4	11.2
South Asia	19.7	14.9	15.0	19.5

Source: U.S. Arms Control and Disarmament Agency, 1995, p. 26.

Fixed-effects Discrete Choice Model

Countries that defect (cooperate) at time *t* are likely to be defectors (cooperators) in period *t*+1. There are two potential explanations for this serial dependence in discrete outcomes that have been emphasized in the literatures (Heckman, 1981). On the one hand, persistence may be the result of 'true' or 'structural' state dependence in which current defection or cooperation directly affects future defection or cooperation.[10]

Alternatively, observed persistence can result from permanent observed heterogeneity across individuals, in that different countries have different underlying propensities to defect or cooperate in all periods. In this later case, current participation does not structurally affect the future propensity to cooperate or defect but rather is a source of serial correlation that can be viewed as 'spurious' state dependence (Chay and Hyslop, 1998).

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[10] Operationally, in a discrete panel data model, the lagged outcome would be included as a determinant of current behavioral responses.

The fixed-effect (e.g. $\varepsilon_{i,t} = \alpha_i$ in Equations (5.4)) approach has some intuitive appeal: permanent unobserved individual effects implies countries have different underlying propensities to arm or disarm in all periods. Such a notions underlies the rationale of the unconditional defectors-the *Wiseguys*-and unconditional cooperators-the *Goodguys*-of Chapter 3's simulations. Arms control policy hinges critically on the ability to credibly estimate the type of state dependence. In the case where current defection does not structurally affect the future propensity to defect, but rather is a source of serial correlation, then changing the incentives through MTCR sanctions can result in disarmament. Conversely, if defection is due to permanent characteristics (e.g. *Wiseguys*), then changing the incentives to defect will have little real effect.

While the econometric literature on probit panel data models is well-established, it is well-known that the probit does not lend itself readily to fixed-effect treatment. In contrast the logit model does lend itself to fixed-effects treatment (Greene, 1993, p. 655). The fixed-effect logit is:

$$\mathbf{Prob(Y_{it} = 1)} = \frac{\mathbf{Exp(\alpha_i + X_{i,t}\beta)}}{\mathbf{1 + Exp(\alpha_i + X_{i,t}\beta)}} \qquad \mathbf{(5.7)}$$

Chamberlain (1980) forwarded a likelihood function conditioned on the number of 1's in the set for each set of T observations. He suggest maximizing the conditional likelihood function, L^c.

$$\mathbf{L^c = \Pi_i\, Prob(Y_{i1} = y_{i1}, Y_{i2} = y_{i2}, \ldots Y_{iT} = y_{iT} \mid \Sigma_t\, y_{it})} \qquad \mathbf{(5.8)}$$

In this form, the countries that always defect (e.g. *Wiseguys*) are always one and contribute nothing to L^c. Likewise, countries that always cooperate (e.g. *Goodguys*) are also zero and contributed nothing to L^c. The *Wiseguys* and *Goodguys* cases contribute nothing because the likelihood function is the product of the probabilities

$$\mathbf{L = \Pi_i\, Prob(Y_{i1} = y_{i1})\, Prob(Y_{i2} = y_{i2}) \ldots\,)} \qquad \mathbf{(5.9)}$$

For each set of T = 31 years has the following probabilities

$$\mathbf{y_{i1} = 0 \text{ and } y_{i1} = 0\ldots \quad Prob(0, 0\ldots \mid sum = 0) = 1} \qquad \mathbf{(5.10)}$$

$$\mathbf{y_{i1} = 1 \text{ and } y_{i1} = 1\ldots. \; Prob(1, 1\ldots \mid sum = 31) = 1} \qquad \mathbf{(5.11)}$$

Clearly, these observations will not and drop out of the likelihood function when we take the log of the probability since the log of 1 is zero. If however, a country cooperates and then defects or visa versa, then

$$\mathbf{Prob(0, 1, 1, 1\ldots 1 \mid sum = 31) \neq 1.} \qquad \mathbf{(5.12)}$$

The product of terms for those countries (i.e. observations sets) for which the sum is not zero or 31, constitutes the conditional logit. While the conditional logit sweeps out the heterogeneity by conditioning on the number of 1's in the set, it may be of interest to test whether there is actually heterogeneity likelihood (Greene, 1993, p. 656). With homogeneity ($\alpha_i = \alpha$), all countries have the same intercept and the model can be estimated with the usual logit.

Under the null hypothesis of homogeneity, both the Chamberlain conditional maximum likelihood estimator (CMLE) and the usual maximum likelihood estimator (MLE) are consistent, but the CMLE is inefficient because it fails to use cases when countries always defect or always cooperate. Under the alternative hypothesis, the MLE is inconsistent, while the CMLE is consistent and efficient.

Ho: CMLE and MLE are consistent, but CMLE is inefficient

H1: CMLE is consistent and efficient, but MLE is inconsistent

The Hausman's test is based on the chi-squared statistic

$$\chi^2 = (\beta_{CMLE} - \beta_{MLE})' (\mathrm{Var[CMLE]} - \mathrm{Var[MLE]})^{-1} (\beta_{CMLE} - \beta_{MLE}) \qquad (5.13)$$

Where β_{CMLE} and β_{MLE} are matrices of coefficients for the CMLE and MLE respectively; and Var[CML] and Var[MLE] are the variance matrix for the CMLE and MLE models respectively.

Table 5.4

Specific Missile Threat Model	Specific Missile Threat Model
CMLE: Equation (1)	MLE: Equation (2)
Conditional (fixed-effects)	Unrestricted
Logistic Regression (N=1016)	Logistic Regression (N=3617)

Variable	B	SE B	Variable	B	SE B
J_1	0.11	0.62	J_1	2.21*	0.23
J_2	1.50**	0.69	J_2	3.97*	0.27
J_3	4.15*	0.99	J_3	4.08*	0.31
J_4	7.11*	1.25	J_4	4.09*	0.30
Area	5.31**	2.37	Area	0.08**	0.04
Borders	-0.33	0.36	Borders	-0.16*	0.05
DC	-2.83*	0.51	DC	-2.30*	0.20
DC^2	0.89*	0.13	DC^2	0.58*	0.04
Milex	-0.01	0.01	Milex	0.02*	0.004
NSAM	1.02*	0.27	NSAM	0.20*	0.01
SAM	2.44*	0.85	SAM	3.10*	0.26
WTO	-0.06	1.03	WTO	1.61*	0.27
Norms	-3.71*	0.91	Norms	-1.26*	0.36
NATO	----	----	NATO	1.28*	0.17
Constant	----	----	Constant	-6.54*	0.50

Note. Pseudo R^2 = 0.63	Pseudo R^2 = 0.57;
L_r =Log Likelihood = -169.57	L_r = Log Likelihood = -830.98
LR $\chi[13]^2 = 573.14$ ($p < 0.00$)	LR $\chi[14]^2 = 2232.12$ ($p < 0.00$)
*$p < .01$; **$p < .05$; ***$p < .1$	*$p < .01$; **$p < .05$; ***$p < .1$

Dependent variable is $Y_{it} = 1$ if country *i* is armed with ballistic missiles in year *t*, an Y_i otherwise for both Equation (1) and Equation (2). LR is the likelihood ratio statistics which evaluates the restricted and unrestricted estimates of the log likelihood. The LR test serves the same function for the maximum likelihood estimation that the F-test serves for least squares: a joint significance tests of the model's coefficients. LR is asymptotically distributed as a chi-squared distribution with the degrees of freedom equal to the number of restrictions being tested LR = $-2[\ln L_r - \ln L_{max}]$. The LR tests whether $[\ln L_r - \ln L_{max}]$ is significantly different from zero. A statistically significant χ^2 value would invalidate the null hypothesis that all of the coefficients are jointly zero. In both equations, we can reject the null hypothesis that the coefficients are zero at 0.001 level of significance. Pseudo R^2 is an informal goodness-of-fit index that measures the fraction of an initial likelihood value explained by the model (see Train, 1986, pp. 91, 167 for more details). NATO omitted in Equation (1) due to no within-group variance.

Table 5.5

Nonspecific Missile Threat Model	Nonspecific Missile Threat Model
CMLE: Equation (3)	MLE: Equation (4)
Conditional (fixed-effects)	Unrestricted
Logistic Regression (N=1016)	Logistic Regression (N=3617)

Variable	B	SE B	Variable	B	SE B
S_1	1.29	2.14	S_1	2.35*	0.43
S_2	1.75	2.12	S_2	2.60*	0.44
S_3	2.88	2.13	S_3	3.95*	0.44
S_4	2.44	2.12	S_4	3.63*	0.45
S_5	4.35**	2.20	S_5	4.79*	0.46
S_6	6.67*	2.43	S_6	5.12*	0.52
S_7	4.48***	2.32	S_7	5.88*	0.53
S_8	7.63*	2.40	S_8	4.14*	0.52
Area	1.39***	0.79	Area	-0.17**	0.04
Borders	-0.18	0.31	Borders	-0.16*	0.53
DC	-3.30*	0.46	DC	-1.46*	0.15
DC^2	1.01*	0.12	DC^2	0.42*	0.04
Milex	-0.01	0.01	Milex	0.02*	0.004
NSAM	1.04*	0.38	NSAM	0.17*	0.06
SAM	3.31*	0.99	SAM	2.99*	0.29
WTO	4.54	1.16	WTO	1.72*	0.26
Norms	-4.04*	0.92	Norms	-1.73*	0.38
NATO	----	----	NATO	1.42*	0.16
Constant	----	----	Constant	-7.89*	0.60

Note. Pseudo $R^2 = 0.59$
Log Likelihood = -184.90
LR $\chi[20]^2 = 542.49$ ($p < 0.00$)
*$p < .01$; **$p < .05$; ***$p < .1$

Pseudo $R^2 = 0.56$
Log Likelihood = -855.82
LR $\chi[21]^2 = 2182.43$ ($p < 0.00$)
*$p < .01$; **$p < .05$; ***$p < .1$

Notes. Dependent variable is $Y_{it} = 1$ if country *i* is armed with ballistic missiles in year *t*, and $Y_{it} = 0$ otherwise for both Equation (3) and Equation (4). NATO omitted from Equation (3) due to no within-group variance. For details of LR and Pseudo R^2 see Notes in Table 5.4.

Results and Interpretation

Table (5.4) shows the results for CMLE model-designated Equation (1) and the MLE model-designated Equation (2). The CMLE dropped 102 countries or 2,681 observations because the country either always armed (sum = 31) or always disarmed (sum =0) throughout T. Casual inspection of Table 5.4 indicates significant differences between the β_{CMLE} and β_{MLE} estimates. The estimated chi-squared statistics verifies that the CMLE is both consistent and efficient: CMLE and MLE $\chi(13)^2 = 75.46$ for equations (1) and (2); CMLE and MLE $\chi(17)^2 = 78.96$ for equations (3) and (4). In both cases, the null hypothesis asserting the consistency of Equations (2) and (4) is rejected at the 1% level; the fixed-effects models, Equations (1) and (2), are consistent and efficient. The following interpretation of the coefficients are based on the CMLE results.

Although the sign and standard errors of the logit coefficients have the same interpretation as the standard OLS, the coefficient *magnitudes* are not elasticities or slopes. Computation of the marginal effects maybe useful when the variable in questions is continuous. But for applications with dummy variables, J_k and S_k the marginal effects may not be meaningful (Greene, 1993, p. 641).

Table 5.6 and Table 5.7 displays the coefficients of the logit conditional fixed-effects regressions as *odds ratios*. The odds ratio for dummy variables is relative to the excluded cases: no defecting neighbors. The odds are defined as the probability of category of a variable compared to the probability of another. The odds are unbounded at the upper end and therefore can take any values greater than zero.

Table 5.6

Specific Missile Threat Model

CMLE: Odds Ratio, Equation (1)

Conditional (fixed-effects)

Logistic Regression (N=1016)

Variable	B	*Odds Ratio*
J_1	0.11	1.11
J_2	1.50**	4.49
J_3	4.15*	63.29
J_4	7.11*	1230.07
Area	5.31**	202.90
Borders	-0.33	0.71
DC	-2.83*	0.59
DC^2	0.89*	2.43
Milex	-0.01	0.99
NSAM	1.02*	2.78
SAM	2.44*	11.43
WTO	-0.06	0.93
Norms	-3.71*	0.02
NATO	----	----
Constant	----	----

*p < .01; **p < .05; ***p < .1

Table 5.7

Nonspecific Missile Threat Model

CMLE: Odds Ratio, Equation (3)

Conditional (fixed-effects)

Logistic Regression (N=1016)

Variable	B	*Odds Ratio*
S_1	1.29	3.63
S_2	1.75	5.77
S_3	2.88	17.85
S_4	2.44	11.53
S_5	4.35**	78.09
S_6	6.67*	787.25
S_7	4.48***	88.36
S_8	7.63*	2061.04
Area	1.39***	4.03
Borders	-0.18	0.84
DC	-3.30*	0.04
DC^2	1.01*	2.75
Milex	-0.01	0.98
NSAM	1.04*	3.01
SAM	3.31*	27.48
WTO	4.54*	94.09
Norms	-4.04*	0.17
NATO	----	----
Constant	----	----

*p < .01; **p < .05; ***p < .1

For continuous variables, the odds ratio is for a one unit increase in the explanatory variable. With the exception of the WTO coefficient the sign and significance of the control variables in Tables 5.6 and 5.7 are approximately the same. The relative size and significance of the coefficients of the strategic variables confirms the a central hypothesis of this research: that missile proliferation is largely an action resulting from local interactions.

Comparing the coefficients of the J_k and S_m dummy variables suggest that geographically proximate missile threats are more important to missile proliferation than threats not necessarily linked to geographic space. Like most physical systems, the forces carrying interactions of particles or molecules decays rapidly with distance (Albin, 1998, p.18). Boulding (1962) presented a common sense assumption that territorial extent of a country is limited by a normal fall off military strength over geographical distance. Such a decline of strength or loss of strength gradient, amounts to a general military disadvantage as the military capability of a nation declines with distance (Quester, 1977). Indeed, the often-quoted first law of geography that 'everything is related to everything else, but nearer things are more related' (Tobler, 1970) captures the essence of the interaction among states: its is the 'nearer' threats that matter the most in ballistic missile proliferation.

First the Specific Missile Threat Model. A country with one defecting neighbor, ($J_1 = 1$) is as likely to defect as a country with no defecting neighbors. The odds a country will defect increase as the number of missile threat increases. When faced with two defecting neighbors, a country is four-and-half times more likely to defect than a country faced with no defecting neighbors. A country with three armed neighbors is more than 63 times more likely to arm than a country with no armed neighbors. When four or more neighbors defect, a country is more than 1,200 times more likely to defect than a country with no armed neighbors.

For the Nonspecific Missile Threat Model, the first four missile threats (S_1 through S_4) are perceived as the excluded case of no missile threats; the fifth threat significantly raises the chances a country will arm. The chances are greater a country will procure ballistic missiles when it faces six missile threats, S_6 as opposed to seven such threats. The chances a country will procure ballistic missiles are the greatest when it faces eight and more missile threats, S_8.

Ballistic missiles and surface-to-air missiles appear to be complements, rather than substitutes. A country with a surface-to-air-missile is eleven times more likely to have ballistic missiles than a country without SAMs. The combination of air defense and offense gives some nations defense against manned aircraft while simultaneously providing a country with a near certain retaliatory (or first strike) capability. An assured penetration capability is a factor of increasing importance as an increasing number of states acquire sophisticated air defenses (Palevitz, 1990). According to one defense analyst "Ballistic missiles become additionally attractive against highly defended targets where manned aircraft may face attrition."[11] Everything else being equal, the odds of defecting increase by 2.78 times for each neighbor with a surface-to-air missile (SAM).

There is no significant difference in military expenditures as percent of total government expenditures between countries with ballistic missiles and those without ballistic missiles. Highly militarized societies are no more likely to procure ballistic missiles than other countries. Warsaw Treaty Organization (WTO) members were no more likely to defect than non-members. NATO variable was dropped from the regression. This suggest that the NATO and WTO alliances had no complementary or

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[11] Director of India's Institute for Defense Studies and Analyses, Air Commodore Singh, quoted in Mahnken (1991, p. 191).

substation effect on ballistic missile proliferation in Europe.[12] International norms arising from missile technology control regime and the associated membership, negatively impacted the chances for defection. A one percent increase in Norms, decreases the chances an unarmed states will arm 50 times (inverse of 0.02).

Signs of the corresponding DC and DC^2 coefficients (-2.88 and 0.88 respectively) are opposite and imply that probability of defecting decreases and then increases with increasing values of DC. These coefficients indicate that countries are unlikely to cooperate with defectors and likely to defect against cooperators. These results are consistent with the gaming models of proliferation discussed in Chapter 2.

The greater a country's land area, the greater are its chances of being 'harm's way' of S_m missile threats. When the J_k dummy variables in Equation (1) are replaced by S_m dummy variables in Equation (3), the Area coefficient odds ratio drops from over 200 to just over 4. Moreover, the significance of the Area coefficient drops from being significant at five percent level in Equation (1) to being significant at the ten percent level in Equation (3).[13]

After controlling for the offensive (J_k dummies) and defensive (NSAM) threats from neighboring states as well as the gains or losses that might arise from defecting against cooperators (*DC* joins) or cooperating against a defector (*CD* joins), the number of borders had no significant impact on ballistic missile procurement. In other words, ballistic missile procurement is not a response to borders *per se* but a response to the threats and opportunities emanating from borders.

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y variable from the regression "due to no within group variance."

[13] The 95% confidence interval for the coefficient of Area in Equation (3) includes zero: [-0.02 to 2.89].

Part II Classic Least Squares Analysis

In the previous section, I showed that the probability of defecting was a nonlinear function of the number of armed neighbors and neighbors capable of striking a state. While this result is consistent with the game-theoretic models presented in Chapter 3, it is restrictive in that it limits a state's response to armed neighbors a binary choice to cooperate or defect. Implicit in the dominant strategy of the multiperson prisoners dilemma model is a mutual defection that involve the acquisition of identical missiles for all countries. In reality, the range, accuracy, and payload of ballistic missiles varies considerably across countries and over time. Intuitively, the variation in missile capability across countries should reflect a state's security requirements.

The Model

In this section I redefine the dependent variable, Y_{it} of Equation 5.4 to be the maximum missile payload of country *i*'s ballistic missile in year *t*. Thus Y_{it} is a continuous variable and can be explained with ordinary least squares (OLS) and avoids the econometric complications encounter with the qualitative choice model.

Consider the following linear regression model:

$$Y_{i,t} = X_{i,t}\,\beta + \varepsilon_{i,t} \qquad (5.14)$$

Where $Y_{i,t}$ is the maximum missile payload capability of country *i*'s ballistic missile; $X_{i,t}$ are the explanatory variables in Table 5.1, β is a vector of coefficients to be estimates, and

$$\varepsilon_{i,t} = \alpha_i + \eta_{it} \qquad (5.15)$$

where η_{it} is assumed to be uncorrected with X_{it}. $E[\eta] = 0$; $E[\eta\ \alpha'] = 0$; $E[\alpha_i] = 0$; $E[\alpha_i, \alpha_i] = \sigma^2$ (constant variance) $E[\alpha_i\alpha_j] = 0$.[14] The first term in equation (5.15), α_i is called an individual effect and reflects two types of ignorance about countries. Firstly, α_i may vary across countries but is constant across time; this part may or may not be correlated with $X_{i,t}$. Alternatively, α_i may vary unsystematically across time and countries and is not correlated with $X_{i,t}$. These individual effects are either *fixed-effects*, that is when α_i is correlated with X_{it} or *random-effects* that is when α_i is uncorrected with X_{it} respectively.

The Random-effects Model

In the random effects model, the coefficients α_i are not fixed in the regression intercept but are allowed to vary over time and space in a random manner. We assume that the individual countries represented by these coefficients have a mean expectation of zero and constant variance under the conditions that $E[\alpha_i\alpha_j] = 0$ for *i* not equal to *j*. Moreover, α_i, X_i assumed to be uncorrelated.

The random-effects model is appropriate when the individual specific constant terms are randomly distributed across cross-sectional units (Greene, 1993, p.469). Random-effects models are often used in situations when the sampled cross-sectional units are drawn from a large population and the researchers wishes to make inferences about the general population based on the sampled units (Kennedy, 1994). The random-effect are appropriate when the data are drawings of observations from a large sample (say thousands of voters) and we wish to make inferences regarding all voters of the

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[14] All expectations are conditioned on X. For more information about the precise nature of the error see Greene, 1993, p. 469-70; Johnston, J., & DiNardo, J., 1997 p. 391-92.

population. Although sample of countries used in my model are nearly exhaustive, several countries have been excluded because of the unavailability of data.[15] While not randomly selected, the sampled of countries are intended to make generalizations about countries not included in the sample.

The major disadvantage of the random-effects model is that it assumes that the random error associated with each cross-section unit is uncorrelated with the other regressors; something that is not like to be the case for the present study. Moreover, the random-effects model assumes that the specification is correct. Suppose, for example, that missile payload is being regressed on payload and the missing variable is circular error probable (CEP), is thought to affect the intercept.[16] Since payload and CEP are likely to be correlated, modeling this as a random-effects will create correlation between the error term and the regressor payload. The result will be bias in the coefficient estimates of the random-effects model.

When the random-effects model is appropriate, OLS will produce consistent estimate of β but the standard errors will be understated; and OLS is not efficient compared to generalized least-squares (GLS) procedure (DiNardo and Johnston, 1998, p. 391). The random-effects model has the advantage that it saves on degrees of freedom relative to the fixed-effects model.

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[15] Milex for several key countries including China, North Korea, USSR and several eastern European countries were not available for each year between 1967 and 1997.

[16] CEP is defined as the radius of the circle around the target within which 50 percent of warheads will fall in repeated firing (MacKenzie, 1990, p. 348).

Fixed-effects Model

The fixed-effects model is a reasonable approach when the difference between units can be viewed as parametric shifts in the regression function (Greene, 1993, p. 469). In such studies the sample includes the entire population, and the model can be viewed as applying only to the cross-sectional units in the study, not ones outside of the sample. My model consist of up to 139 countries and is nearly exhaustive of the countries in the world. While my model seems more suited to the fixed effects approach, the dummy variable approach is costly in terms of degrees of freedom lost. On the other hand, the fixed-effects estimation solves the problem of omitted variables by 'throwing away' some of the variance that contaminates the random-effects estimator (DiNardo and Johnston, 1998, p. 399).

Results and Interpretation

Tables 5.8 presents the results for the fixed and random effects estimation of Equation (5.14). Casual observation reveals that the coefficients of the two estimates do not substantially different in magnitude.

Countries often compensate their missile inaccuracy with more destructive warheads.

Table 5.8

Fixed-effects Regression

Equation (5) (N=3617)

Dependent Variable is Payload

Random-effects GLS Regression

Equation (6) (N=3617)

Dependent Variable is Payload

Variable	B	SE B	Variable	B	SE B
J_1	-26.03	23.74	J_1	-23.08	14.27
J_2	128.43*	35.25	J_2	140.77*	18.35
J_3	365.43*	41.97	J_3	369.99*	23.53
J_4	489.37*	51.73	J_4	479.61*	22.71
Area	61.76*	4.02	Area	55.85*	6.42
Borders	-94. 53*	18.86	Borders	-77.64*	7.05
DC	-41.28*	13.34	DC	-35.70*	9.00
DC^2	18.71*	1.64	DC^2	16.93*	1.25
Milex	0.92	0.39	Milex	0.89*	0.23
NSAM	18.72*	5.16	NSAM	16.83*	3.60
SAM	42.40*	15.82	SAM	53.05*	11.64
WTO	-79.37	1.40	WTO	-28.67	33.71
Norms	-11.97	17.64	Norms	-13.28	20.47
NATO	-10.16	1.05	NATO	1.89	41.99
Constant	-323.37*	111.33	Constant	-331.79*	77.37

Note. Adjusted $R^2 = 0.76$
F(14, 3469) = 348.48 (p<0.0)
Standard errors are robust

R^2 within = 0.30
R^2 between = 0.30
R^2 overall = 0.36
Wald $\chi[14]^2 = 1551.42$ (p < 0.0)
*p < .01; **p < .05; ***p < .1

The F-stat and Wald χ^2 test the null hypothesis that the coefficients are jointly zero. The goodness-of-fit measure indicates that the fixed-effect model explains 76 percent of the variation in payload. The GLS corresponding goodness-of-fit measures are derived from regressing estimated payloads on actual payloads-R^2 overall; regressing estimated mean values of payload on actual payloads-R^2 within; and regressing the difference between estimated payloads and estimated mean payloads on actual payloads. For further details, see STATA, 1997, p. 634-635.

Hausman Test

Under the null hypothesis of no correlation between the regressors and error term, both the OLS fixed-effects model and the GLS random-effects model are consistent, but fixed-effect is not efficient. The alternative hypothesis is that the fixed-effects model is consistent but the random-effects model is not consistent. Consequently, if the two estimates differ systematically, we can reject the orthognality assumption. The Hausman's test is based on the following chi-squared statistic:

$$\chi[K]^2 = (\beta_{OLS} - \beta_{GLS})' (V_{OLS} - V_{GLS})^{-1} (\beta_{OLS} - \beta_{GLS}) \qquad (5.16)$$

where OLS is the fixed-effects estimator and GLS random-effects the generalized least square estimator, K is the number of regressors (excluding the intercept) and V is the variance matrix for the respective estimators. A significant χ^2 would be evidence against the null hypothesis.

$$\chi[14]^2 = 1.64 \qquad (5.17)$$

Equations (5.17) suggest the null hypothesis of no correlation between the regressors and the error term cannot be rejected and that GLS estimation is consistent. The following discussion therefore uses the coefficients from the GLS estimates, Equation (5), Table 5.8.

The inclusion of a constant makes interpretation of the dummy coefficient is straightforward. The average maximum payload for countries without any armed neighbors is –331.79 kg the intercept variable. Countries change the maximum missile payload according to the number of armed neighbors which is represented by the difference between the intercept and the coefficient of the dummy variables J_k dummy variables. Countries with two armed neighbors, the average maximum missile payload is

140.77 kg higher than a countries without any armed neighbors; countries with three armed neighbors, the average maximum payload is 370 kg higher than countries without *any* armed neighbors; countries with four and more armed neighbors, the average maximum payload is 479.62 kg higher than the maximum payload for countries without any armed neighbors; the missile payloads in countries with one armed neighbor were no different from countries without any armed neighbors. This is all to say that the critical tipping point at which the feedback transitions from disarming to arming, is ***between*** having one and two armed neighbors: countries with less than one neighbor decrease their missile payloads while countries with two and more neighbors increase their missiles payloads.

The significance and sign of the coefficients of Area, J_k, SAM, NSAM, DC and DC^2 are consistent with the conditional fixed-effects logistic regression coefficient Table 5.4, Equation (1). Land area in Equation (4) serves as a proxy variable for the number of non specific missile threat, S_m. Larger countries are more likely than smaller countries to be in the range of non contiguous threats. In other words, bigger countries are more likely than smaller countries to be "in harm's way" of the S_m missile threats. A one square kilometer in land area increases missile payloads increase by nearly 20 kg (ceteris paribus).[17] Holding constant the number of cross-border missile threats, maximum missile payloads decrease by roughly 77 kg for every border. This result seems counterintuitive. However, it may be reasoned that once a country's national security objectives are satisfied (e.g. gains/ loses from unilaterally defecting-DC, unilateral cooperation-CD, and mutual defection-J_n), there is a predisposition to reducing missile payloads vis-à-vis

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[17] Every exp(1) square kilometer or exp 2.731 sq. km missile payload increases by 53.05 kg or 53.05/2.71 = 19.55 kg/ km.

bordering neighbors. The average country in the sample had 4.04 borders. Therefore, a country without any armed neighbor can be expected to *decrease* its maximum missile payloads by approximately 4.04 x 77.64 = 313.66 kg, which is close the value of the intercept.[18]

Ballistic missile payloads increase by more than 16 kg for each bordering state with surface-to-air defense missiles (SAM). This is result consistent with the longstanding historical practice of increasing the of power offensive weapons to overcome existing defense (e.g. cannons versus castle walls and tanks versus forts). Ballistic missile payloads in countries that are also armed with surface-to-air missiles, are on average, 53 kg heavier than in countries without SAMs. Although payloads are much more sensitive to offensive threats from neighboring ballistic missiles, the SAM results challenge the prevailing conventional wisdom on the stability of defensive weapon.

While international norms against ballistic missile proliferation are large and significant, they are insufficient to over-ride micro-level behavior. Furthermore, international norms have had no significant impact on missile payloads. Indeed, Figure 1.4 of Chapter 1, shows that payloads of ballistic missiles have increased between 1987 and 1997 despite the MTCR. Export controls have not been effective in stopping the deployment of more advanced systems despite the Regime's Category II guidelines which explicitly restrict the transfer of missile subsystems and parts that might be used to increase a rocket's accuracy, range, and payload capacity.[19] Consequently, international norms could obstruct the transfer of missile technology among states. Instead, the

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[18] Recall, the intercept takes the value of the excluded varibale-J_0 category– a country without any armed neighbors.

[19] Components usable for warhead safing, fusing, and firing mechanisms are subject to outright export prohibition, even if ostensibly requested for use in civilian space programs (Nolan, 1993, p. 35).

coefficient of Norms indicates that international norms have had no significant impact missile payload. New domestic missile production may explain why missile payloads are unresponsive to MTCR norms. The MTCR is a regime regulating the international trade of missile technology; it does not directly regulate *domestic* ballistic missile innovations. Since 1987, the inaugural year of the MTCR, India, Pakistan, China, Iran, and North Korea have all tested domestically produced ballistic missiles IRBMs with payloads capacities well beyond the MTCR guidelines.

The coefficients of NATO and WTO indicate that the payloads of the ballistic missiles in the arsenals of these two alliances did not differ significantly from other countries. This result makes sense in light of the fact that many of the ballistic missiles deployed outside of Europe, are American or Russian-made weapons and should not differ significantly from those deployed in Europe.

The coefficient of Milex in Equation (1) indicates that military expenditures as a percentage of government expenditures did not significantly impact the probability a country acquired ballistic missiles. In contrast, the coefficient of Milex in Equation (5) indicates that more militarized countries had slightly heavier missile payloads than countries that allocated relatively small amounts of government expenditures to military expenditures. The estimated mean payload increased by 0.89 kg for each additional increase in military expenditures as a percentage central government expenditures, everything else being equal. Although the coefficient of Milex is statistically significant, the small slope implies the differences in payload due to military expenditures is not strategically significant. Table 5.3 shows the difference in ME/ CGE between in the

Middle East and East Asia regions is roughly 41% which translates into approximately 37 kg difference in missile payloads-between the missile payloads in these two regions.

In Tables 5.9 and 5.10 repeats the fixed and random-effects the previous regressions analysis with the dependent variable defined as the log of payload +1 and log of range +1 respectively. The purpose of the log transformations is to guard against heterosckedascity. The payload values range from 0 to 2000 kg and the range values range from 0 to 3500 km. I added one to each observation so as to retain the zero payload and zero range cases after the logarithmic transformation. An interaction variable SAMxNSAM is included to examine how neighboring defensive weapons systems interact.

Application of the Hausman test reveals the GLS is consistent in for both the payload and range equations:

$$\chi[14]^2 = 1.08 \tag{5.18}$$

$$\chi[14]^2 = 0.97 \tag{5.19}$$

respectively.

One interesting difference between the range and payload result is the change in significance of the Norms coefficient: the coefficient is significantly negative (as was the case in the previous model) in the payload equation but insignificant in the range equation. This difference can be attributed in part to general negative connotation implied with terms like ‘weapons of mass destruction’. WMD included chemical, biological and nuclear weapons and carry with them a negative image.

Table 5.9

Fixed-effects Regression

Equation (7) (N=3617)

Dependent Variable is Log Payload

Random-effects GLS Regression

Equation (8) (N=3617)

Dependent Variable is Log Payload

Variable	B	SE B	Variable	B	SE B
J_1	-0.133	0.134	J_1	-0.106	0.095
J_2	0.670*	0.215	J_2	0.715*	0.122
J_3	2.433*	0.284	J_3	2.491*	0.155
J_4	3.302*	0.264	J_4	3.336*	0.151
Area	0.715*	0.296	Area	0.555*	0.043
Borders	-0.400*	0.135	Borders	-0.485*	0.049
DC	0.013	0.125	DC	0.014	0.059
DC^2	0.101*	0.016	DC^2	0.091*	0.008
Milex	0.003***	0.002	Milex	0.003*	0.001
NSAM	0.091**	0.037	NSAM	0.080**	0.037
SAM	0.298*	0.116	SAM	0.355*	0.106
SAMxNSAM	0.524	0.049	SAMxNSAM	0.054	0.041
WTO	-0.878***	0.476	WTO	-0.718*	-0.226
NATO	0.001	0.074	NATO	0.358	0.289
Norms	-0.560*	0.154	Norms	-0.581*	0.135
Constant	-6.321*	0.812	Constant	-4.210*	0.540

Note. Adjusted $R^2 = 0.825$
F(15, 3468) = 113.92 ($p<0.0$)
Standard errors are robust
*p < .01; **p < .05; ***p < .1

R^2 within = 0.34
R^2 between = 0.33
R^2 overall = 0.33
Wald $\chi[15]^2 = 1845.27$ ($p < 0.0$)
*p < .01; **p < .05; ***p < .1

Table 5.10

Fixed-effects Regression

Equation (9) (N=3617)

Dependent Variable is Log Range

Random-effects GLS Regression

Equation (10) (N=3617)

Dependent Variable is Log Range

Variable	B	SE B	Variable	B	SE B
J_1	-0.143	0.118	J_1	-0.123	0.080
J_2	0.582*	0.183	J_2	0.648*	0.103
J_3	1.938*	0.246	J_3	1.971*	0.131
J_4	2.848*	0.252	J_4	2.833*	0.127
Area	0.458*	0.026	Area	0.395*	0.370
Borders	-0.460*	0.115	Borders	-0.430*	0.418
DC	0.027	0.106	DC	0.038	0.505
DC^2	0.081*	0.014	DC^2	0.075*	0.007
Milex	0.001	0.001	Milex	0.001	0.001
NSAM	0.051	0.032	NSAM	0.414	0.032
SAM	-0.044	0.121	SAM	-0.002	0.089
SAMxNSAM	0.135*	0.048	SAMxNSAM	0.141*	0.035
WTO	-0.425	0.419	WTO	-0.247	0.191
NATO	-0.092	0.057	NATO	0.168	0.24
Norms	0.103	0.131	Norms	0.081	0.111
Constant	-3.199*	0.703	Constant	-2.660*	0.460

Note. Adjusted $R^2 = 0.831$
$F(15, 3468) = 65.94$ ($p<0.0$)
Standard errors are robust
*$p < .01$; **$p < .05$; ***$p < .1$

R^2 within = 0.347
R^2 between = 0.400
R^2 overall = 0.392
Wald $\chi[15]^2 = 1935.13$ ($p < 0.0$)
*$p < .01$; **$p < .05$; ***$p < .1$

Conclusions

I argued in Chapters 2 and Chapters 3, that ballistic missile proliferation is a dynamic process that can be explained in part, by states' response to threats to their national security; the present Chapter marshals compelling evidence to support this claim. I show that ballistic missile proliferation arises largely out of micro-level interactions among states. Macro-level factors like NATO or Warsaw Pact alliance membership had no significant effect on missile proliferation. While international norms did have a significantly negative impact on proliferation, they did not offset the state's response to local neighborhood missile threats; international norms had no impact on preventing missile payload upgrades.

The impact surface-to-air missiles have on ballistic missile proliferation is contrary to what conventional wisdom would predict: instead of enhancing security defensive missiles actually give rise to not only proliferation but missile innovations as well. While a offensive response to defense is not new and in fact has around since at least the Middle Ages (Quester, 1977). In recent years several nations have deployed air-defense SAMs such as the *Patriot-3* and *Arrow* in hopes of being able to shoot down incoming ballistic missiles. Although its too early to tell if these defensive systems will be technologically effective enough to dissuade potential aggressors, *Patriot-3* deployment does not appear to have prompted states to retire their ballistic missile arsenals. If anything, the response to antimissile systems had been more missiles with deadlier payloads (see Conclusion section of Chapter 6). Harvey's (1992) cost-benefit analysis provides a plausible theoretical explanation why might antimissile systems might be destabilizing. His main result is that ballistic missiles are only cost-effective when delivering a nuclear payload.

Along with the certainty of and the dis-utility (or penalty for aggression) from retaliation, ballistic missiles can deter aggression. The advantage ballistic missiles over manned combat aircraft, Harvey (1992) argues is that former can penetrate air defense. However, when the penetrability of ballistic missiles is reduced, the ability of nations to retaliate is also reduced. To offset this loss of certainty a country can simply increase the number of missiles beyond the number of antimissile interceptors and/ or increase the dis-utility or penalty for aggression with deadlier payloads. The Conclusion section of Chapter 6 discusses these possibilities in greater detail.

Controlling ballistic missile proliferation with a suppliers cartel like the MTCR has had some unintended consequences. While the Regime has been credited with terminating programs like the *Condor*, a collaborative project involving Egypt, Iraq, and Argentina, it has been less successful in scaling back missile programs in North Korea, Iran and other developing countries. Countries wishing to encourage commercial domestic production often intentionally thwart foreign suppliers with trade barriers and trade restrictions that favor indigenous production. This policy, conventionally known as import substitution, is an economic development strategy that has had mixed results. Nonetheless, the MTCR's restrictions North-South technology transfers may have encouraged developing countries to substitute indigenous missile production for missile imports. It probably is no accident that the countries now capable of producing ballistic missiles domestically have at one time faced an international arms embargo (See Table 1.2 in Chapter 1).

CHAPTER 6

Ballistic Missile Proliferation: A Self-Organizing Phenomenon

Social science is built on the understanding of systems and that systemic effects that arise from the unintended consequences of complex interactions (Jervis, 1997). Unfortunately, the basic concept of a system is frequently ignored the analysis of weapons proliferation. Contemporary weapons proliferation literature often examines ballistic missile proliferation on a country-by-country basis. While case studies can be very informative, they cannot be aggregated or generalized to ascertain the stability of the international system.

Seeking to understand how ballistic missile proliferation affects the international system by looking at countries separately seems inappropriate for several reasons. First of all, the response to missiles threats are multilateral rather than bilateral. As Chapter 5 shows, the chance a country defects depends upon the number of defecting neighbors as well as the number of non-contiguous missile threats. Secondly, the response to missile threats is nonlinear: the response to three armed neighbors on payload was more than three times the response of one armed neighbor. The payload response to missile threats is in effect analogous to increasing returns-output that is proportionately more than the input it receives over some range. John Hopfield (1982), who discovered a similar type of response in neural networks of the brain, pointed out that this kind of nonlinear response creates a dynamic *system* that can in effect processes information.

A systemic approach to ballistic missile proliferation seems appropriate. This perspective maintains that the international system has properties distinct from its individual parts. Following simple and uncoordinated strategies the parts can produce aggregate behavior that is complex and ordered, although not necessarily predictable and stable. This does not imply an absence of regularities. As Jervis stressed: "the systems approach is the belief that structures matter and that the internal characteristics of the elements matter less than their place in the system" (Jervis, 1997, p. 11). This is why very different kinds of countries (e.g. democracies, dictators, theocracies, etc) all have ballistic missiles. Indeed, Chapter 5 concluded the degree to which a society is militarized is not a significant predictor of ballistic missile proliferation.

Jervis (1997, p. 6) defines a system as "a set of units or elements interconnected so that changes in some elements or their relations produce changes in other parts of the system and the entire system exhibits properties and behavior that are different from those parts. A system's parts are often called agents because they have the basic properties of information transfer, storage and processing. An agent could be a household in a city, a firm or a consumer in an economy or a country in the international system.[1]

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[1] Nicholson (1989, p. 25) defines the international system as a set of relationships which cross state boundaries. Given this definition, the agents become any whose attributes are affected by events that go on outside of the state's borders.

Complex Systems

Complex systems are those that have many components, many feedback loops among those components, and multiple interconnections among subsystems (Jervis 1993, p. 9). Interconnections permit disruptions in one part of a system to propagate. Chapter 4 used the join count statistics to show that missile proliferation was spatially dependent and linked to geographic contiguity. Connections are also constraints that need not be physical linkages such as borders. In the regression models of Chapter 5, the contiguous as well as non-contiguous missile threatens created interconnections among countries.

Connections imply that agents' actions can have multiple effects upon one another. For instance, an arms race between India and Pakistan cannot be understood without paying attention to Taiwanese and Russian armaments, which both presumably would impact India's armament levels via China. Similarly, the adoption of one weapon often requires changes in other weapons, in tactics, and in some cases-in strategies and interests (Jervis, 1997).

Complex systems evolve in ways that make predicting their future configuration from an original configuration, intractable. Even simple deterministic laws can generate very complicated and even random motions (Berry 1991).[2] Complex systems undergo "change which is not describable by a single rule nor are reducible to only one level of explanation, any level of which might include features whose emergence cannot be predicted from their current specifications" because some complex systems are so

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[2] Henri Poincare showed that an eclipse of the Moon could be predicted one thousand years in the future. However, a lunar eclipse could not be predicted in one million years (which is a relatively short-time by astrological terms) even though the motion of the Sun, Moon, and Earth are strictly governed by exact laws (Schroder, 1991; Jervis, 1997).

unstable that the course of their trajectories depends on initial conditions (Kirshbaum, 1998).

While the basic components of many complex systems are quite simple it is the interactions of the many parts which gives rise to complexity (Wolfram, 1988). Herbert Simon notes that, "given the properties of the parts and laws of their interactions, it not a trivial matter to infer the properties of the whole."[3] For instance, the U.S. Constitution empowers the Executive, Legislative and Judicial branches of the federal government yet each branch's power is checked by the authority of the remaining two. While the branches themselves are pretty complicated entities, government, which is even more complex, emerges from the routine interaction of the branches.

A ballistic missile may be considered as an assemblage of a number of interconnected and interacting systems (e.g. guidance, propulsion, re-entry vehicle etc.) that perform distinct functions in accomplishing the missile's mission. While these subsystems are themselves the subject of sophisticated engineering analysis, the in-flight performance of a ballistic missile cannot be strictly ascertained through scientific knowledge or techniques that studies the subsystems separately.[4]

The first *Atlas* rocket engines were rated at 135,000lbs of thrust-a figure that was readily attainable on the test stand but which proved to be elusive once the engine was interconnected to the plumbing and propellant tanks of the actual missiles (Perry, 1964, p. 151).[5]

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[3] "Coming up: The Debate America Wanted." *New York Times*, Nov. 3, 1988.

[4] Although computers have greatly improved the predictive powers of missile designers, computer simulations do not yield the knowledge equivalent to in-flight testing. One recent report on the aerospace industry productivity cites the industry-wide practice of substituting computer simulations for testing as being one of the contributing factors to quality problems. "People issues are cracks in aerospace industry foundations". *Aviation Week & Technology*, June 21, 1999, pp. 63-66.

[5] For the operations *Atlas* engine, a thrust increase of 25% was necessary.

Greek sophist Zeno, presents an interesting paradox, which illustrates the limitations and inadequacies of static equilibrium analysis. An arrow's flight, which coincidentally follows a ballistic missile trajectory, viewed at any point along its trajectory is stationary. Since the arrow's flight consist of an infinite number of points, each of which is stationary, its movement is an illusion.

Ostensibly, Zeno was trying to show the absurdity of understanding a system by studying its parts. By focusing attention on the parts separate from the whole, the phenomenon of flight becomes and illusion.

Emergence

The difference between the parts and the system is often expressed as the emergent properties of the latter (De Vany, 1996). Emergence means that there is no code for higher-level dynamics in the lower parts (Green, 1993). Emergent structures appear without explicit pressure or instructions from outside the system. In other words, identifiable structures emerge from complex systems without being its intentions. De Vany (1996, p.433) identifies three necessary conditions for emergence.

i. collection of agents who follow instructions
ii. interaction among agents forms macroscopic patterns
iii. an observer {economist} who interprets the pattern as a structure/process

Emergence is a functional characteristic of complex systems. Atoms search for a minimum energy state by forming chemical bonds with each other, thereby becoming the emergent structure known as molecules. Human beings try to satisfy their material needs by buying, selling, and trading with one another, thereby creating an emergent structure known as a market (Waldrop, 1992, p. 288). It seems reasonable to speculate that an analogous model of international relations would share similar features: people seek to promote their survival and security by guaranteeing the availability of resources, thereby creating an emergent structure known as a country.[6] The most prominent version of 'balance-of-power' theory argues that international stability emerges not from the fact any particular state desires stability but from competitive interaction among states with conflicting goals (Waltz, 1979).[7] Hence, outcomes in the international system, much like prices in a competitive market, "often do not correspond with the intentions of any particular actor, even the most powerful ones" (Jervis, 1993, p. 31). Chapter 4 shows the emergence of spatial autocorrelation in the process of missile proliferation.

In the international system, each state arrives at policies and decisions according to its own internal process; no central processing or global signals is permitted. As Waltz (1979, p. 96) put it, they "develop their own strategies, chart their own course, make their own decisions." In describing ballistic missile proliferation, Navias (1993, p. 37) contends an analogue process exist in the international system. He argues that each state "...has its own particular motivations and objectives in acquiring ballistic missile systems, as each country's defense planners seek to find solutions to their own particular security dilemmas and threats. It is therefore not unreasonable to assume that in each state a different weight is attached to the various rationales for supporting ballistic missile acquisition."

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[6] Japan in the 1930s, which relied heavily on resources outside its borders sought to expand the area it controlled (Manchuria, China, and Indonesia). This policy was driven by the fear that an adversary might deprive the Japanese of these vital resources. To remain secure, Japan needed unfettered access to raw materials and markets.

Self-Organizing Systems

The most provocative claim of complex theory is that complex systems often exhibit spontaneous properties of *self-organization*. Starting from disordered initial conditions, some complex systems autonomously evolve into highly ordered states. Any system that takes a form that is not imposed from outside (by walls, machines or forces) can said to be self-organize. As few as two parts (as in magnetic or gravitational attraction) are sufficient for self-organization.

Some hint of self-organization was seen in the simulation experiments of Chapters 3: Starting with a random allocation of armed and unarmed sites, the lattices self-organized themselves into an ordered structure in which armed countries were spatially concentrated. Although the lattice system was perturbed with different initial conditions, (e.g. invading *Goodguys* and *Wiseguys* strategies) a similar equilibrium structure emerged. Starting with the equivalent of a random distribution of joins, Chapter 4 shows that a highly regular pattern of *positive* autocorrelation emerges as ballistic missile spread throughout Asia, Europe, the Middle East and North Africa.

In 1987, Bak et.al. proposed theory of self-organized criticality (SOC) to explain the tendency of self-organizing systems to "naturally evolve into a critical state in which a minor event starts a chain reaction that can affect any number of elements in the system" (Bak and Chen, 1991, p. 46). Experimental evidence of SOC has been found in cellular automata, sand pile, and earthquakes (Bak, 1996), traffic flows (Nagel and Paczuski, 1995) and economic fluctuations (Takayasu, Hirabayashi, and Hamada, 1992). According to the theory, "the mechanism which produces minor events is the same that

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[7] There is a long tradition of assuming the origins of the state as to lie in the requisite of survival, with the ability to wage war: Carneiro (1970); Bean (1973); Tilly (1975).

leads to major events." Such systems never reach a stable 'equilibrium' but instead spontaneously evolve toward a critical state and return to it even if perturbed an external shock.

Economists Scheinkman and Woodford (1994) applied the SOC principles to model firm inventories. In their model, firms producing intermediate and final goods comprise a multi-layered input-output economy. An order for a final good, will on occasion, produce a chain reaction of orders for intermediate goods. The extent of the chain reaction depends on level of inventories: if inventories are high, orders will typically be met out of stock and will not trigger additional orders, if inventories level are low, each order will give rise to two additional orders (Krugman, 1996). In other words, there is a critical inventory level, which gives rise to a chain reaction or avalanche in production.

World politics is marked by sudden and unpredictable events that dramatically alter the course of human affairs. An assassination, a new weapon, a plague, the downing of a plane – all can trigger outcomes that change the course of world politics. On April 6, 1994, unknown assailants fired a surface-to-air missiles (SAM) at a plane carrying the presidents of Rwanda and Burundi – Juvenal Habyarimana and Cyprien Ntaryamira as it landed at Kilgali. The plane crashed into Habyarimana's own garden, killing all on board and triggering a wave of ethnic violence in which hundreds of thousands of Rwandans died (Nossal, 1998).

Feedback is central to the way complex systems behave. Feedback occurs when a change in one element or relationship often affects other elements, which in turn affects the original element. *Positive* feedback occurs when change in one direction sets in motion reinforcing pressures that produces further change in the same direction.). Arms racing is a classic case of positive feedback; if a rival state increases arms, its primary opponent will increase its arms too, leading to spiraling levels of arms in both arsenals. The Prisoners' Dilemma (PD) and SSM gaming models discussed in Chapter 2 are examples of positive feedback in ballistic missile proliferation. In the PD case, positive feedback trapped both India and Pakistan in a costly arms race. In the SSM model, positive feedback culminated in the War of the Cities campaign in which Iraq and Iran pounded each other's cities with hundreds of ballistic missiles. In these examples positive feedback seemed to reinforced instability. Feedback is *negative* or dampening when change triggers forces that counteract the initial change and return the system to its original position. In the equilibrium outcome of Chicken, a player is better off cooperating if he knows with great certainty the opponent intends to defect. For Israel and Saudi Arabia (see Chapter 2), negative feedback (the former cooperating with the latter's defection), allowed both nations to avoid the disastrous outcome of war.

Measuring Complexity

The predictability of interactions of very many states are the most difficult to unravel (Waltz, 1979). Since interactions give rise to complexity in systems, quantifying systems interactions seems an appropriate way to characterize complexity. Complexity has been measured by logical depth, metric entropy, information content, fluctuation complexity and various other techniques (Decker and Milne, 1997). One method of measuring complexity is to treat the world as a system and count the ways countries, the units of the system, can interact with one another. Consider a field of three countries {A, B, C}. They have no contractual or alliance relations with one another nor do they stand independent of one another; their status is completely unspecified. What strategy will they select in order to capture the optimal security? In other words, how will they react with one another to ensure their survival as states? When considering three distinct nations ('A', 'B', and 'C') the number of possible interaction structures is five:

$$\{\{A, B\}, \{A, C\}, \{B, C\}, \{A, B, C\}, \{\phi\}\}$$

The empty set is included here to represent the participation constraint (De Vany 1996). A's missiles could target only B (or visa versa) or both A and B could be armed and target one another. I designate {A, B} to represent the three possible ways A and B can interact. Similarly, C's missiles could only target A's territory (or visa versa) or both A and C could be armed and target one another {A, C}. A similar logic applied to the pairing of B and C's interaction. A, B or C's missiles could strike the remaining two nations (or all capable of striking all) {A, B, C}. Finally, A, B, and C could be all armed and incapable of striking one another or simply all disarmed {ϕ}.

Jervis (1997, p. 127) notes that as "the number of actors increases, the paths of interaction in the system multiply and become extremely intricate." Indeed, the subset of possible interactions explodes as the as the number of countries increases.

The difficulty in estimating the set of interactions that will emerge is directly related to the number of countries considered. Bell's number tells us the number of ways of agents can interact. Bell's number has no closed form and must be computed recursively. With only 3 countries there are 5 possible interaction structures; with 12 there are 4.23 x 10^6 interaction structures. Table 6.1 summarizes the possible interactions for *n*-countries. Clearly, the task of predicting which structure will emerge is intractable. If an 'equilibrium structure' emerges among the many possibilities one would like to know what characterizes the 'equilibrium structure' and how the agents go about achieving it (De Vany, 1996).

Table 6.1

Possible interstates interactions among *n*-countries

n-countries	Possible Interactions Structures
3	0.5 x 10
6	2.03 x 10^2
12	4.23 x 10^6
24	4.45 x 10^{17}
44	8.70 x 10^{39}
64	1.72 x 10^{65}
104	3.83 x 10^{121}

Source: DeVany (1996)

Another convenient way of conveying this aspect of complexity is through maps. The simplest map that can be produced is binary map in which countries are designated C if they cooperate or D if they defect. For a given number of countries the number of possible arrangements is given by Equation 6.1

$$\begin{matrix} N \\ k \end{matrix} = \frac{N!}{k!\,(N-k)!} \tag{6.1}$$

Where N = number of countries and k = number of defectors. With only 50 countries and five defectors, the number of possible maps is roughly 2, 096, 897.

Modeling Complexity with Cellular Automata (CA)

Many complex systems are difficult to examine or model using conventional optimization techniques. The difficulty arises from the enormous size and complexity of the search space. Traditionally, arms procurement and weapons innovation has been seen as the outcome of rational optimization. One meaning of optimization is that every agent selects a unique strategy that dominates every other strategy. Selection of a dominant strategy requires pair-wise comparisons among all strategies in the interaction space. The number of potential strategies that must be considered can seem intractably large. For example, suppose a player must choose one of two actions: cooperate or defect in a local subgame with eight neighbors. If the information set is limited to just the immediate past plays of neighboring participants, there are still 2 exp(2 exp(9)) mappings from the information set to the set of actions (Albin, 1990). The task of enforcing consistent strategies among the agents makes optimization intractable. If the search space is large and complex, the notion of optimizing may have no operational meaning (DeVany, 1996).

The *a priori* assumptions of an 'equilibrium' solution to the problem in which "all agents *ex ante* can subscribe and which makes their strategies consistent is a leap of methodological faith" (Silverberg et.al., 1988, p. 1036). Alternatively, researchers often study complex system with computer algorithms known as cellular automata or CA.[8] A cellular automaton consists of a one, two or three-dimensional array of identically programmed automata or cells with a finite set of possible values (Wolfram, 1984; Green, 1993).[9] Each cell takes on *k* possible values (e.g. $k = 1$ for armed cell or $k = 0$ for an unarmed cell), and is updated in discrete time steps according to rules that depend on the value of sites in some neighborhood (Wolfram, 1985). That is, the status of the cell at a given time step depends on its own state and one time step previously, and the states of its nearby neighbors. The status of the entire lattice advances in discrete time steps because the cells in are updated synchronously. Two common configurations for two-dimensional CA are the five and nine neighborhood:

N	N N N
N C N	N C N
N	N N N
Von Neumann Neighborhood	Moore Neighborhood

Figure 6.1 Cellular Automata Neighborhood types.

In the von Neumann configuration the center cell C interacts with the four nearest neighbors; in the Moore configuration the center cell interacts with the eight closest cells. In a full lattice, the cells label N would also have four and eight neighbors respectively. The von Neumann configuration has an intuitive theoretical and practical appeal: the average number of borders for the sample of 139 countries used in the empirical analysis of Chapter 5, is 4.02.

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[8] Cellular automata have great research advantages: they are cheap, easy to program on computers and have a wide-range of nonlinear applications (Albin, 1998, p. 17).

[9] Arrays forms either a one-dimensional string of cells; a two-dimensional grid or a three-dimensional solid. Most often the cells are arranged as a rectangular grid, but other configurations such as a honeycomb are also used.

The status of each cell is determined by a set of rules that instruct each cellular automaton on when to change its status. The rules are typically simple and apply equally to every cell. Despite their simple construction, cellular automata are capable of self-generating complex behavior. Wolfram (1984, 1985), and Bossomaier and Green (1998) provide some examples of complex self-generated patterns from a two-dimensional cellular automaton lattice. Cellular automata have successfully replicated complex system dynamics including: dendrite crystal growth, reaction-diffusion systems, and turbulent flow pattern.

The Game of Life

The Game of Life is one of the most well known CA applications.[10] John Conway created Life as a simple "universe" capable of computation. Conway produced a grid where each cell could be in one of two states: on or off or alive or dead. The rules of Life are:

1. A living cell with only 0 or 1 living neighbors dies from isolation
2. A living cell with 4 or more living neighbors dies from congestion
3. A dead cell with exactly three living neighbors becomes alive
4. All other cells remain unchanged

Despite these simple rules complex patterns autonomously emerged. Life is typical of the way in which many cellular automata reproduce features of living systems (Green, 1998).[11]

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[10] "Life" originally began as an experiment to determine if a simple system of rules could create a universal computer. The concept "universal computer" was invented by Alan Turing and denotes a machine that is capable of emulating any kind of information processing by implementing a small set of simple operations.

[11] Life tends to spontaneously develop 'organisms' consisting of a clustering of cells, the same way that natural law in some unknown way leads to more complex systems. Indeed, Life has been suggested to mimic aspects of the emergence of complexity in nature (Gardner, 1970).

Cellular Automata Simulation of Ballistic Missile Proliferation

I simulate ballistic missile proliferation using cellular automata algorithms. Two types of boundary constraints are imposed upon the lattice edges: open and periodic. These boundary conditions are commonly used in the literature. Open boundary conditions might be more appropriately for modeling geographic regions that are physically separated from other regions of the world by deserts or oceans (e.g. Sub-Saharan Africa and South America). Here, interactions among states are essentially constrained by the geography. In contrast, periodic boundary conditions define the lattice such that it resembles a torus, which is intended to mimic the globe or a sphere.

Two boundary conditions are used to explore how the lattice system responds to complex feedback loops. The feedback loops are greater in the periodic boundary conditions configuration because opposite edges of the lattice are connected to one another. The appendix of this manuscript details the technical aspects of open and periodic boundary constraints.

I model the missile proliferation with a von Neumann neighborhood because the countries used in the regression analysis had an average of four international borders. Moreover, the coefficients on the J_n dummy variable exceeded the coefficients of the S_k dummy variables, indicating that countries took contiguous threats more seriously than non-contiguous threats.

Simulation 1: Ballistic Missile Payload with Open Boundary Conditions

Repeated interactions with neighbors are likely to have consequences beyond cooperation or defection; particularly in arms racing circumstances. The regression analysis of Chapter 5 is summarized in Table 6.2 and shows that countries react to additional missile threats by increasing their missile payload. In Simulation 1, all cellular automata adhere to the following rules.

Table 6.2

Summary of Regression Results and CA Rules

	Armed Neighbors	**Coefficient**	**t-stats**	**CA Rules**
Constant	0	-331.79	-4.29	Deducts a random integer between zero and ten from the payload.
J_1	1	-23.08	1.62	Does not change its missile payload.
J_2	2	140.77	7.66	Adds a random integer between zero and ten to its current missile payload.
J_3	3	369.99	15.72	Same as two neighbors
J_4	4 *and more*	479.62	21.19	Same as three neighbors

Notes. See Equation 5.4, Table 5.8, and Chapter 5 for full regression summary.

Initially, ten percent of the sites are randomly armed with positive payloads between one and ten and the remaining sites are given payloads between zero and negative 10. These payload seedings are nominal payloads, and do not reflect any actual weight in pounds or kilograms. The negative payloads are included to show the cumulative effect of mutual cooperation over time. Ostensibly, negative missile payloads do not exist, however, the regression analysis of Chapter 5 does provides some empirical justification for this designation.

Negative (and zero) missile payloads not only represent unarmed sites but 'peaceful threats' to contiguous neighbors. Conversely, *positive* missile payloads represent armed sites with the conventional 'hostile threat' to contiguous neighbors. The greater the payload magnitude, the greater the intensity of the missile 'threat'.

Ballistic missiles themselves are complex systems composed of many smaller interacting subsystems from which a flight vehicle emerges. These subsystems interact in ways that make missile performance a stochastic process. I incorporate chance into the model by allowing the missile payload to randomly increase or decrease by a random number between –10 and + 10.

Figure 6.2-A shows the initial configuration. Sites colored in deep blue are unarmed and have the highest negative payloads –10. Conversely, sites with brown shading are armed sites with the highest positive payload +10. States with near zero payloads are shaded light green. The remaining sites are shaded in a continuum of colors representing the relative magnitude of their initial payloads. The exact payload numbers in the initial configuration are printed in matrix form in Figure 6.2-B.

The lattice evolves according the **CA Rules** in Table 6.2. After approximately 50 generations (not shown), a distinctive pattern emerges in which sites are in one of three states: (1) shaded deep blue and are increasing negative payload (2)-shaded deep red and are increasing positive payload or (3) shaded light green and are stationary or unchanging payload.

Figure 6.3-A and Figures 6.3-B display the evolution of the system after 100 generations. All feedback in this configuration is positive: stationary sites (light green) border the arming (red) sites and separate them from the unarming (blue) sites. [12] Given a different set of initial conditions, an entirely different pattern emerges yet the colors arrange themselves in the relatively same spatial ordering: a red core with a light-green semi-periphery and deep blue periphery. This alerts us to the path dependent nature of the emergence: three different patterns evolve from three separate random seedings. Path dependence means that outcome is dependent upon a particular sequence of events. In path dependence analysis, if you change one or more element(s) in the sequence, the outcome is likely to be different (Nossal, 1998). In other words, there are many possible outcomes depending on the initial conditions. For example, had Ayatollah Khomeni come to power a few years later, Iran would have likely had nuclear capable ballistic missiles. [13] These missiles might have been enough to discourage Iraq from attacking Iran following the imposition of a Western arms embargo on the former. A nuclear-armed Iran under Khomeni would have almost certainly provoked Saudi Arabia, Kuwait, Iraq, and possibly the United Arab Emirates to arm with comparable weapons.

The simulation model is intended to portray a *qualitative* result and does not represent geographical representation of world and missile proliferation *per se*. However, Figure 6.3 does capture crucial aspects of the phenomenon. First of all, the spatial ordering of armed (core) and unarmed sites does bare a strong resemblance to ballistic

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[12] The open boundary conditions are not shown in Figure 6.3 or Figure 6.4. In the final configuration, the edge site have zero payloads and would be light-green.

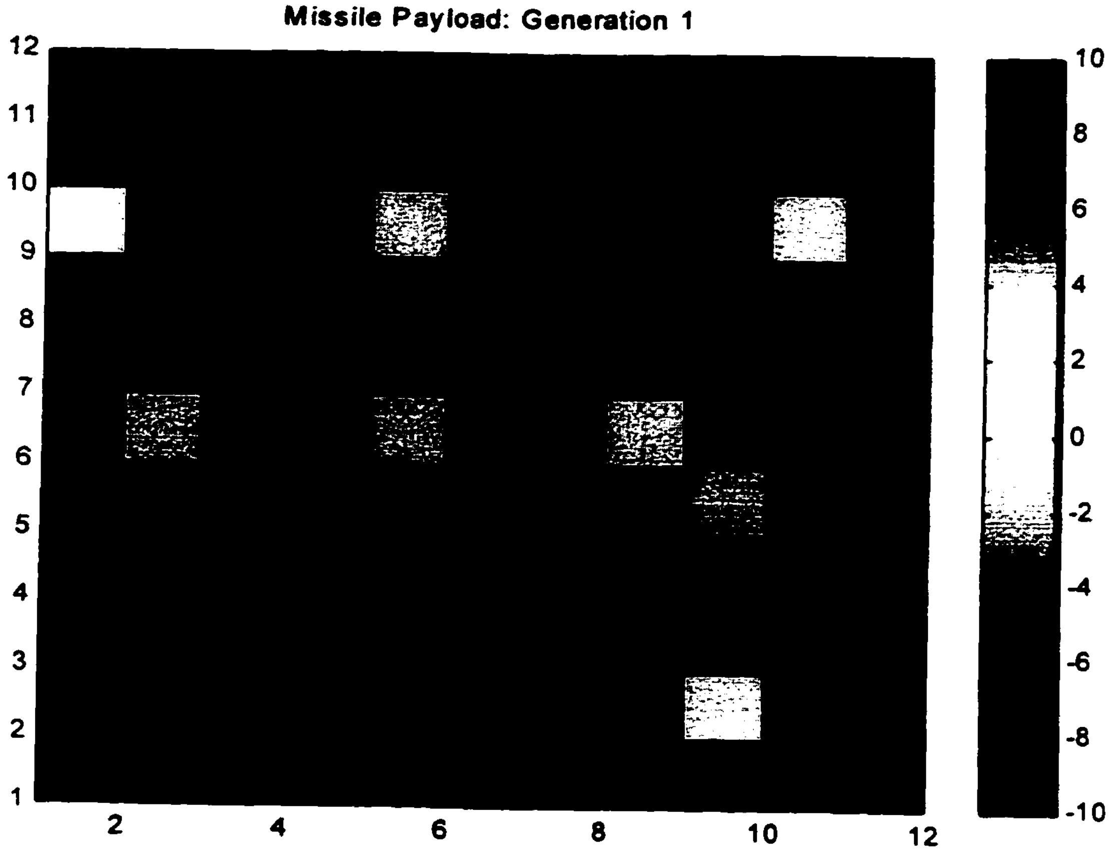
[13] Documents discovered in the US Embassy in Tehran after the fall of the Shah indicate that in the 1970s the Israelis were interested supplying Iran with a missile (Navias, 1993, p. 85). One of six oil-for-arms deals between the Shah and Israeli Defense Minister Shimon Perez, included a 'ground to ground missiles that ... can be regarded also as a missile with a nuclear head ...'. "Document details Israeli Missile deal with the Shah". *New York Times* April 3, 1986.

missile proliferation in the real world. In fact, the three armed zones in Figure 6.3–A might correspond to Europe, the Middle East, and Asia (from left to right). The core powers in Europe would correspond to West Germany, France, Russia (USSR) with Italy, Greece, Turkey, Scandinavia, and Eastern Europe in the semi-periphery ; in the Middle the core powers might be Israel, Iraq, Syrian, Iran, Saudi Arabia, and Egypt with Libya, United Arab Emirates, Afghanistan, Turkey and the Sudan in the semi-periphery and in the Asia the core power might be, India, China, Russia (USSR) with the Koreas, Japan and Taiwan in the semi-periphery. All other nations comprise and are geographically clustered together and are shaded deep blue in Figure 6.3-A.

How Figures 6.3 –A changes, if perturbed depends on which sites change. If site 536 (in bold) [10, 9] in Figure 6.3 –A arms, the lattice undergo a dramatic change that would initiate a change reaction that would ultimately arm 18 additional sites:

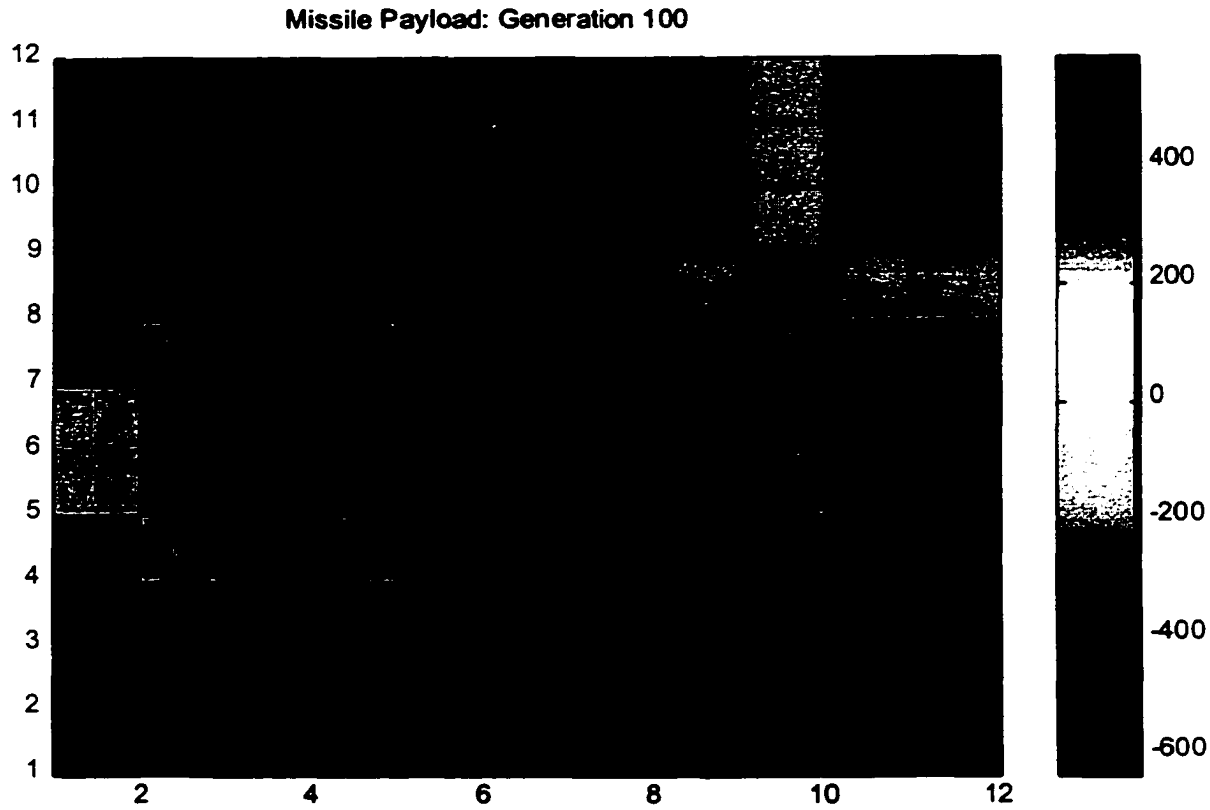
[8, 12], [8, 11] [8, 10] [11, 12], [11, 11], [11, 10] [11, 8], [11, 8], [11, 6]
[9, 12], [9, 11] [9, 10] [12, 12], [12, 11], [12, 10] [12, 8], [12, 7], [12, 6]

Criticality in the international system implies that attention should be paid to the behavior of events that might start a chain reaction that could lead to catastrophe. On this count, conventional wisdom's emphasis on the so-called 'rogue state' seems warranted. However, equally important in this matter are the actions of the more 'main stream' states. If say, Japan were to independently develop a ballistic missile from its *H-2A* civilian launcher in response to North Korea's *Taepo Dong* missile threat, China, Russia, and the Koreas would be in its range. How these targeted states responded could have dramatic consequences in North Asia and beyond.



-8	-4	-4	-3	-8	-4	-5	-9	-1	-2	-3	-3
-8	-4	-4	-7	-7	-5	-2	-2	2	-5	-7	-7
-6	-4	-7	-8	-8	-3	-10	-10	-1	-3	-3	-3
-2	-7	-5	-5	-6	-10	8	-4	-5	-6	-7	-7
-5	-4	-5	8	-7	-3	-7	-7	1	-7	-5	-5
-6	1	10	-4	1	-9	-9	2	-9	-8	-4	-4
-10	-8	-10	-6	-10	-7	9	-6	-9	-2	-6	-6
-5	-4	-9	-7	-7	-1	-2	-2	-1	-1	-6	-6
2	-2	-5	-5	1	-6	-3	-6	-1	3	-4	-4
-2	-9	-9	-3	-7	-8	-1	-5	-9	-5	4	4
-6	-7	-10	4	-1	-4	-9	-10	-8	-5	9	9
-6	-7	-10	4	-1	-4	-9	-10	-8	-5	9	9

Figure 6.2 Initial Payload Configuration: Generation 1. Each cell color corresponds to a nominal missile payload ranging from -10 to 10 demarcated on the colorbar to the right. The numerical payloads values are displayed in a 11 x 11 matrix. The lattice is indexed by grid points 1 throughout 12. Open boundary conditions are not displayed.



-557	-527	-526	-547	-564	-558	-521	-556	-514	-527	-537
-555	-544	-543	-636	-534	-541	-523	-574	-517	-539	-538
-526	-568	-503	-530	-548	-578	-556	-542	-483	-576	-559
-501	-11	-9	-18	-568	-529	-31	-8	-548	-551	-545
-16	569	566	558	- 8	-50	546	502	-12	-515	-531
-6	512	552	536	-9	-23	484	582	-8	-565	-535
-551	-8	-10	-17	-546	-7	529	551	-19	-553	-509
-540	-596	-523	-558	-550	-495	-2	-6	**-536**	-1	-9
-506	-491	-545	-555	-511	-523	-537	-502	-1	553	512
-552	-571	-604	-560	-526	-562	-540	-543	-16	529	557
-550	-521	-523	-525	-526	-527	-555	-567	-30	472	527

Figure 6.3 Final Payload Configuration: Generation 100. Each cell color corresponds to a nominal missile payload ranging from -600 to 600 demarcated on the colorbar to the right. The numerical payloads values are displayed in a 11 x 11 matrix. The lattice is indexed by grid points 1 throughout 12. Open boundary conditions are not displayed.

Simulation 2: Ballistic Missile Payload/ Periodic Boundary Conditions

Simulation 2 refines Simulation 1 by incorporating periodic boundary conditions and the marginal effects of missile payload from the regression analysis of Chapter 5.

Table 6.3

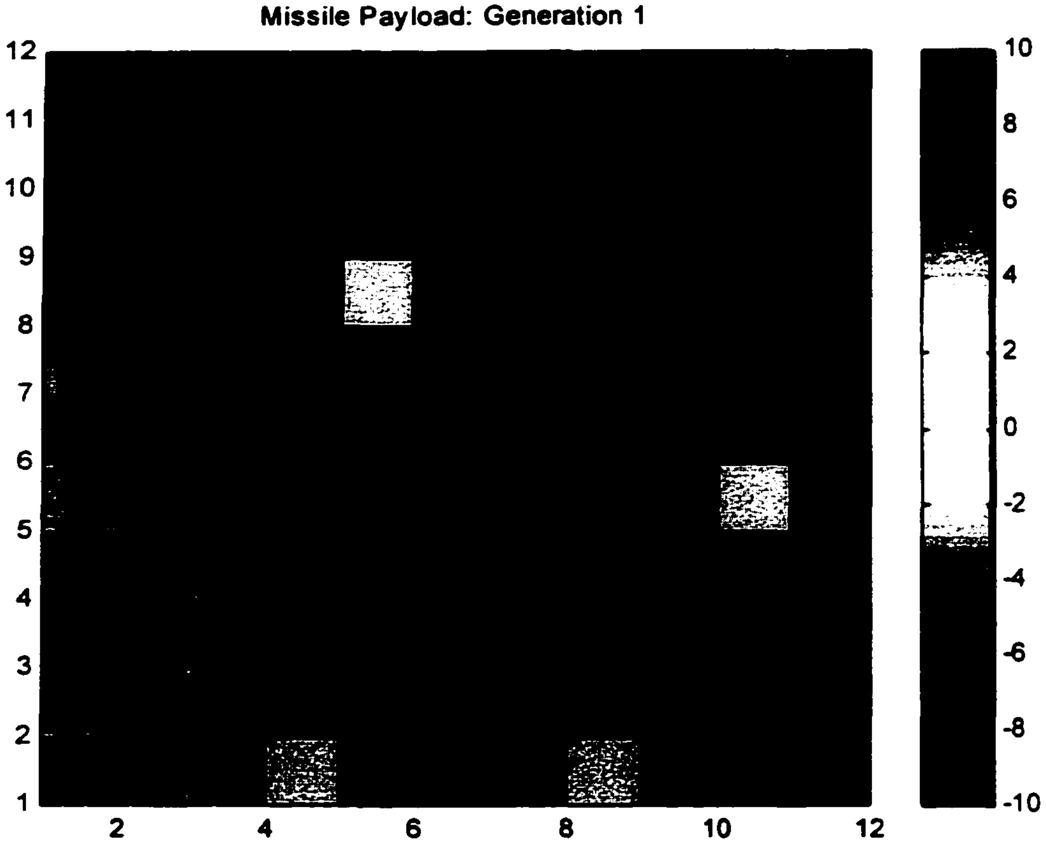
Summary of Payload Regression Results and Factors (N=3617)

Variable	**Armed Neighbors**	**Coefficient**	**t-stats**	**Factor**
Constant	0	-331.79	-4.29	331/23 ≅ -14
J_1	1	23.08	1.62	23/23 = 1
J_2	2	140.77	7.66	140/23 ≅ 6
J_3	3	369.99	15.72	369/ 23 ≅ 16
J_4	4 *and more*	479.61	21.19	479/23 ≅ 20

Table 6.3 summarizes the coefficients of the dummy variables from Table 6.2. The final column of Table 6.3 normalizes the coefficient to the J_1 coefficient, 23.08. I chose to re-scale the coefficients to J_1 to remain consistent with the rules of Simulation 1. The resulting 'Factor' is rounded off to the nearest whole number remain consistent with prior C programming code developed thus far. The CA in this simulation obey the following rules:

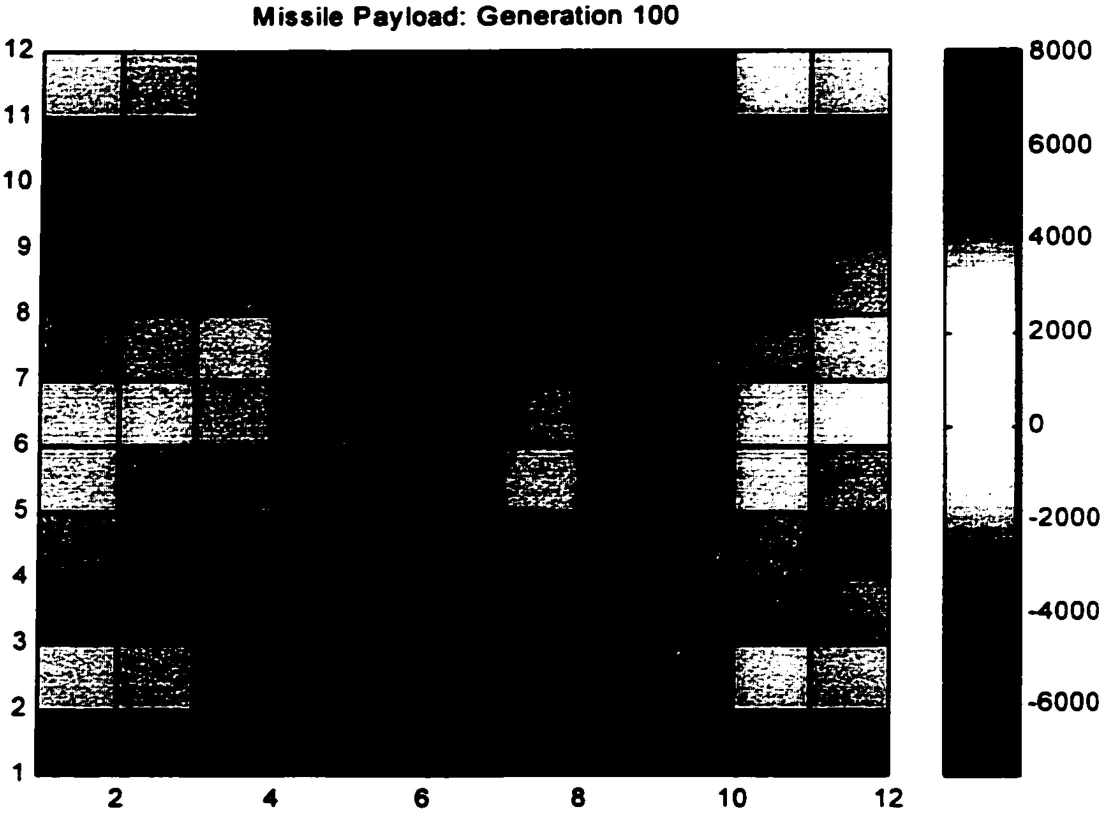
1. a site with no armed neighbors (e.g. neighbors with zero or negative payload) deducts a *14 times* a random integer between zero and ten from the payload of its missile in the following period
2. a site with *one* armed neighbor (e.g. one neighbor with a positive missile payload) does not change its missile payload
3. a site with *two* armed neighbors adds *6 times* random integer between zero and ten to its current missile payload
4. a site with *three* armed neighbors adds *16 times* random integer between zero and ten to its current missile payload
5. a site with *four* or more armed neighbors adds *20 times* a random integer between zero and ten to its current missile payload

Figure 6.4 shows the initial configuration. Again, the lattice self-organizes into clusters of dynamic armed and unarmed sites, with static unarmed sites ringing the dynamic armed sites. However, unlike the open boundary case, some arming and unarming sites share a single border. Figure 6.5 shows the lattice retains this stable configuration after 100 time steps. The payloads in the periodic boundary condition case are an order of magnitude higher than the open boundary conditions. Arguably, much of this increase in payload and spatial complexity is due to the systemic feedback of the torus structure. Periodic boundary conditions increase the system level interactions by feeding back the missile payloads at the edge of the lattice. Unlike the open boundary conditions, which treats the edges of the lattice as infinite sinks, the torus structure conserves and transmits edge site interactions. This feedback also seems responsible for the increase in armed sites relative to the open boundary condition case.



```
 -8   -1   -9    3   -2   -3   -1    1    5   -6  -10
 -1   -1   -2   -3   -5   -8   10   -2   -5   -9   -6
 -4   -9   -9   -5   -1  -10  -10   -3   -6  -10   -6
 -9   -9   -1   -6   -7   -5   -2   -6   -4   -5   -5
 -1   -7   -9   -9   -1   -3    8   -5    4    1   -6
 -8   -9   -6   -5   -5   -3   -6   -5   -2    8   -9
 -1   -4  -10   -6   -5   -8   -3   -9   -4   -7   -1
 -2   10    5   -4    2   -1   -2   -3   -9   -2   -3
 -7  -10   -6   -1   -8   -8   -6   -1   -1  -10   -9
 -8    6  -10   -4   -6   -4   -5    9    7   -6  -10
```

Figure 6.4 Initial Payload Configuration: Generation 1. Each cell color corresponds to a nominal missile range ranging from –10 to 10 demarcated on the colorbar to the right. The numerical payload values are displayed in a 11 x 11 matrix. The lattice is indexed by grid points 1 throughout 12.



```
-7052   -6582   -6355   -5898   -6748   -6481   -7087   -5936   -6171   -7052   -6582
 2280    2552    7713    7443    7071    7819    6779    7164    7503    2280    2552
-470    -159    -123      -6     -91    -284    -270    -424    -361    -470    -159
-3      -6607   -6020   -6868   -6102   -6117     -85     -33      -3      -3   -6607
 2702      -2    -121   -7491   -6210    -207    2554    7799    8080    2702      -2
 2507    2640    2778    -124   -6390      -7    2836    6980    7584    2507    2640
-39      2860    2636    -105   -6549   -6580      -9      -8    -130     -39    2860
-6365      -8     -13   -6115   -6426   -6422   -6464   -6331   -6049   -6365      -8
-498    -6428   -6991   -6495   -7132   -6707   -6558   -6619   -6963   -6498   -6428
-7052   -6582   -6355   -5898   -6748   -6481   -7087   -5936   -6171   -7052   -6582
 2280    2552    7713    7443    7071    7819    6779    7164    7503    2280    2552
```

Figure 6.5 Final Payload Configuration: Generation 100. Each cell color corresponds to a nominal missile payload ranging from –10 to 10 demarcated on the colorbar to the right. The numerical range values are displayed in a 11 x 11 matrix. The lattice is indexed by grid points 1 throughout 12. Periodic boundary conditions are displayed.

Power Laws and Self-Organizing Systems

A power law essentially says that there is a distribution of results such that the larger the effects, the less frequent it is seen. Many self-organizing systems exhibit power law behavior. Bak , Chen, and Creutz (1989) show that the 'Game of Life' self-organizes into a critical state, characterized by a distribution of live cells which conforms to power laws.[14] The distribution of earthquake activity is example of a power law: there are many small earthquakes but very few large ones.[15] Krugman (1996, p. 43) argues that power law relationships are the result of three basic things: First, the objects being studied are subject to substantial growth over time. Secondly, the growth rate of any individual object is random, so that over time a wide range of different sizes emerges. Thirdly, the expected growth rate over time is independent of scale: large objects grow no faster or slower than smaller objects.

A commonly used approach to examine power laws is the rank-size distribution. The rank-size distribution is a modified form of the Pareto Distribution and is generally expressed as follows:

$$\mathbf{M_R = m_1 / R^{\alpha}} \qquad \textbf{(6.2)}$$

This is the Lotka form of the distribution in which $\mathbf{M_R}$ represent the say missile range, **R** represents the rank of a missiles (rank 1 referring to the longest range missile), and α is a constant which indicates the rate at which the missile range decreases with rank. Graphically, if both axes are scaled logarithmically, the rank-size distribution is represented by a down-ward sloping straight line (strictly speaking a set of points) with

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[14] Defining the total activity of the lattice as s, the number of births and deaths following a single perturbation, Bak et.al. (1989) show s to be distributed as a power law, $D(s) \sim s^{-\phi}$ where $\phi = 1.4$.

[15] In 1956, Geologists Beno Gutenberg and Charles Richter, for who is famous for devising the Richter scale, discovered that the number of large earthquakes is related to the number of small ones-known as the

intercept m_1 and slope of α. The availability of data catalogued in the Nonproliferation Review (1994, pp. 183-186) permits us to empirically characterize the range and payload distributions for ballistic missiles of all sizes.[16] Figure 6.6 shows a log-log plot of rank and range for ballistic missiles of all ranges in 1994. Table 6.4 shows OLS estimates of the intercept $m_1 = 11.92$; slope of $\alpha = 1.66$; and Adjusted R-squared = 0.92. Figure 6.7 shows a log-log plot of rank and payload for ballistic missiles of all payloads in 1994. Table 6.5 shows OLS estimate of the intercept is 9.75; the slope is 0.9; and Adjusted R-squared equals 0.68.

Missile range distribution conforms to power law behavior but missile payload distribution does not. Missile payload measurements do not necessarily reflect the *yield* or destructiveness of a missile's warhead. For instance, the *Scud B's* payload capacity is 1000 kg. As originally configured, the *Scud* can either carry conventional or nuclear payloads. Future research might consider the distribution of missile yield as opposed to missile payload.

Missile range conveys interactions and intentions in ways that payloads do not. And as such, range reflects not only a country's security preferences, but also conveys (intended and unintended) threats to neighboring states. For instance the ability to fire missiles at U.S. bases in Japan is an important goal of North Korean. Despite any evidence showing that North Korea's ballistic missiles had been 'nuclearized', Japanese Vice Defense Minister Akira Hiyoshi described Pyonyong's missile capability as Japan's top security threat (Hayes, 1991, p. 148).

Gutenberg-Richter law (Bak and Chen, 1991).

[16] This research is limited to missile ranges under 3,500 km (see Chapter 1). Longer range missiles such as ICBMs and SLBMs have not proliferated beyond a few states and are therefore not part of contemporary ballistic missile proliferation. However, this does not preclude the emergence of long-ran missiles from the

Moreover, ballistic missiles can be quite destructive, payload notwithstanding. The damage caused to Teheran by the *Al Husayn* missiles during the 1988 War of the Cities campaign, while far from catastrophic, was not insignificant (Navias, 1993). Seth Carus (1991, p. 35) contends that the damage caused by 4 tons of metal traveling more than 2500 mph at impact was formidable:

> "missiles fired at Baghdad and Teheran ... caused tremendous damage seemingly out of proportion to the size of the warhead. In some cases, entire streets and shops and houses were destroyed. In other instances reinforced concrete skyscrapers were devastated by missile strikes. The missiles left craters at least 10 meters across and several meters deep."

How did the range distribution come about? We can propose a scenario in which an initial distribution of missile ranges worldwide undergoes changes that increase or decrease the missile ranges. While these changes are for the most part deliberate and in response to a state's security needs, chance plays a central role in not only missile procurement but missile innovation as well. If this were not the case, countries could embark on ambitious weapons projects without fear of failure. Successful missile production and innovation are particularly dicey even for the established powers. Karp (1996) enumerates a long list of technical hurdles associated with rocket development and concludes that building a long range missiles "it is anything but easy. Almost any country can build small artillery rockets ..." but at ranges greater than 1000 km "the technical requirements become progressively more demanding." Successful rocket development is contingent upon a numerous of factors.

There is no simple 'road map' to successful missile development. While missile programs are unique, all are also constrained by the nature of the technology itself. Hard

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complex interactions of the states considered.

technologies for missiles less than 150 km are widely available, while those for systems with ranges above 1000 km are demanding for all but a handful of regional powers to master (Karp, 1996, p. 145).

Missile proliferation is process that also depends on chance. Proliferation may be likely but is in no sense inevitable (Karp, 1996, p. 6). The spatial autocorrelation analysis in Chapter 4 assumes that the join types between countries arise from a stochastic process. Recall that the join counts categorizes international borders according to a country's missile status and the missile status of its bordering neighbors. Joins or border can be one of four types: mutual defection DD; mutual cooperation CC; unilateral defection DC or exploitation, CD. Spatial analysis traditionally combines the number of CD joins with the DC join count.

Figure 6.8 through Figure 6.11 shows log-log plots of rank and DC joins for 1967, 1977, 1987 and 1997. The slope and intercept remain relatively constant over these decades despite the collapse of the Soviet Union in 1991 and the emergence of newly independent states in Eastern Europe and Central Asia during the early 1990s. The political upheaval that accompanied the end of the Cold War dramatically altered the number of geopolitical borders (see Chapter 1). Yet these changes had relatively little impact on the distribution of DC joins in 1997.

Figure 6.6 The Rank-size Distribution Applied to Missile Ranges

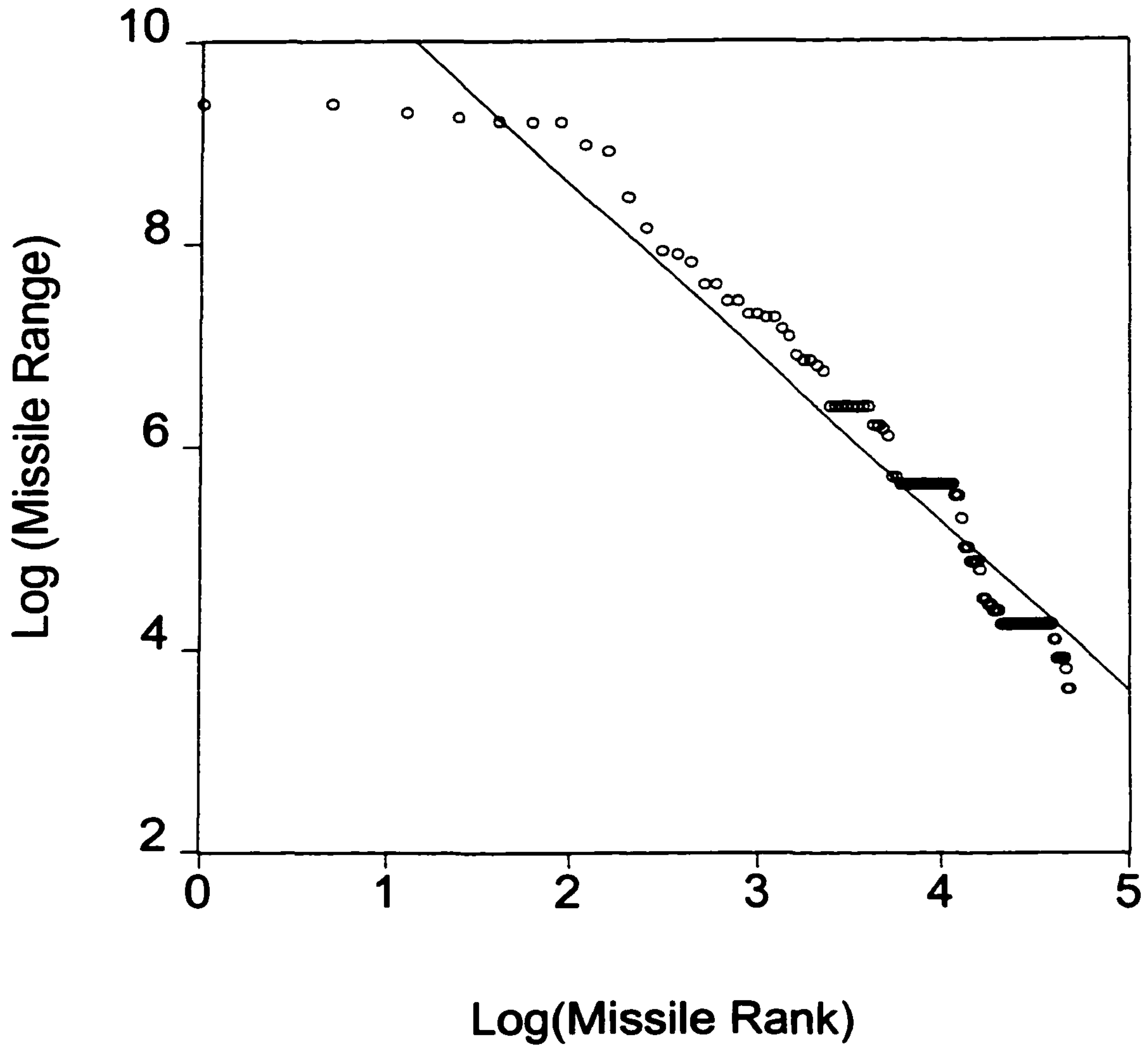

Table 6.4

OLS Estimates of Range Intercept and Slope

Dependent Variable: Log(Range)
Observations: 108

Variable	Coefficient	Std. Error	t-Statistic
C	11.92	0.17	69.07
Log(Rank)	-1.66	0.04	-36.89
Adjusted R-squared	0.93	F statistic = 1361.54	

Figure 6.7 The Rank-size Distribution Applied to Missile Payloads

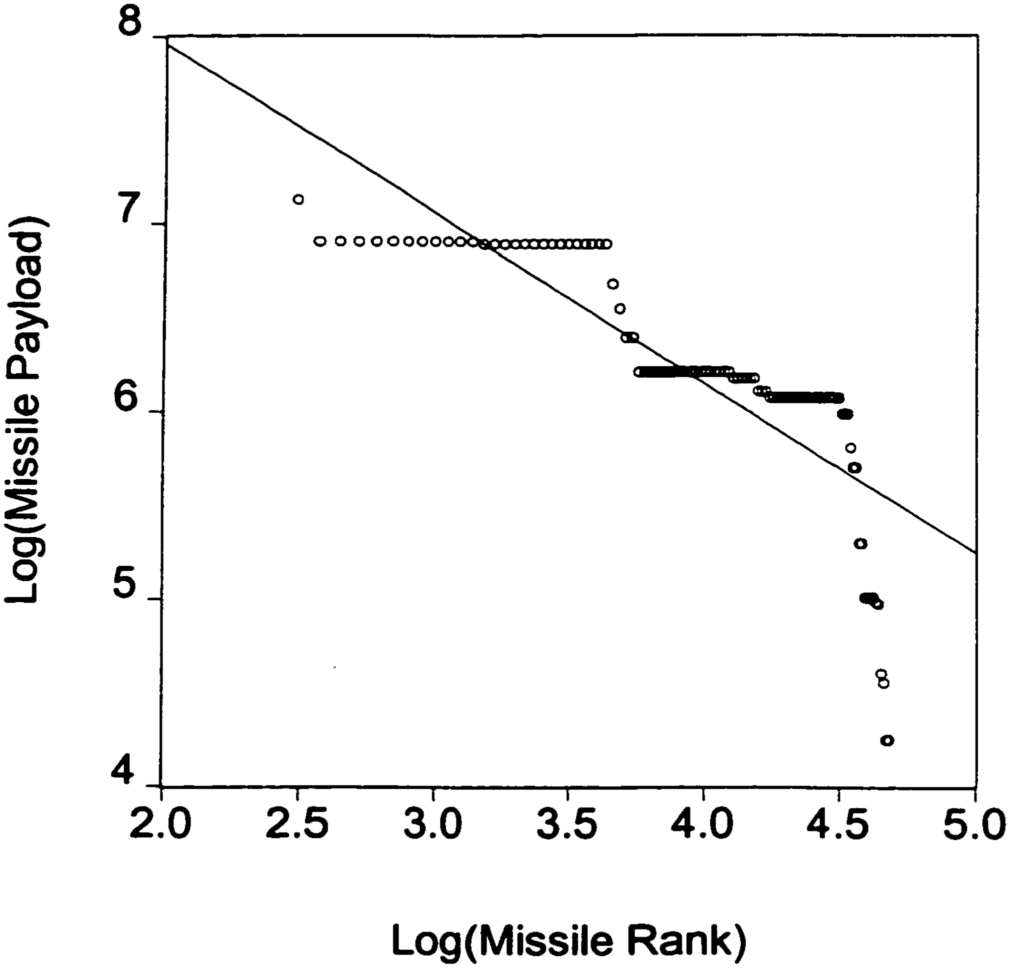

Table 6.5

OLS Estimates of Payload Intercept and Slope

Dependent Variable: Log(PAYLOAD) Observations: 97 Variable	Coefficient	Std. Error	t-Statistic
C	9.76	0.25	38.86
Log(RANK)	-0.90	0.06	-14.34
Adjusted R-squared	0.68	F-statistic = 205.86	

Figure 6.8 The Rank-size Distribution Applied to DC Joins in 1967

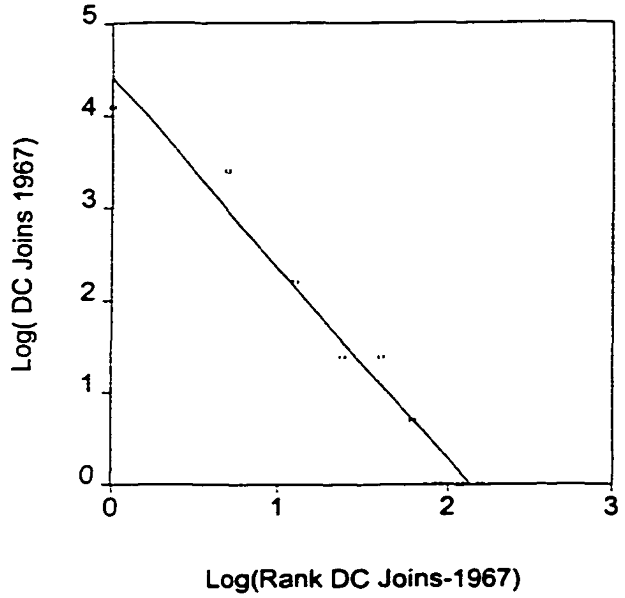

Table 6.6.

Intercept and Slope
DC Joins - 1967

Intercept	4.40 (19.75)
Slope	-2.06 (-14.60)

Adj. $R^2 = 0.96$
$N = 9$

t-stat in parenthesis

Figure 6.9 The Rank-size Distribution Applied to DC Joins in 1977

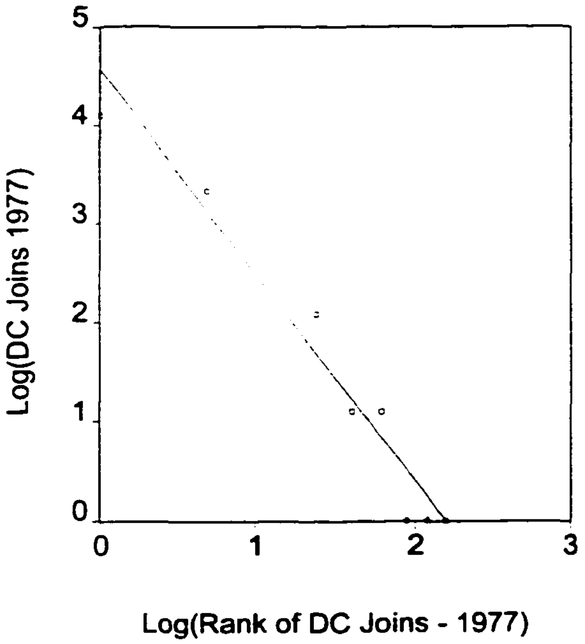

Table 6.7.

Intercept and Slope
DC Joins - 1977

Intercept	4.45 (15.45)
Slope	-2.07 (-11.10)

Adj. $R^2 = 0.96$
$N = 9$

t-stat in parenthesis

Figure 6.10 The Rank-size Distribution Applied to DC Joins in 1987

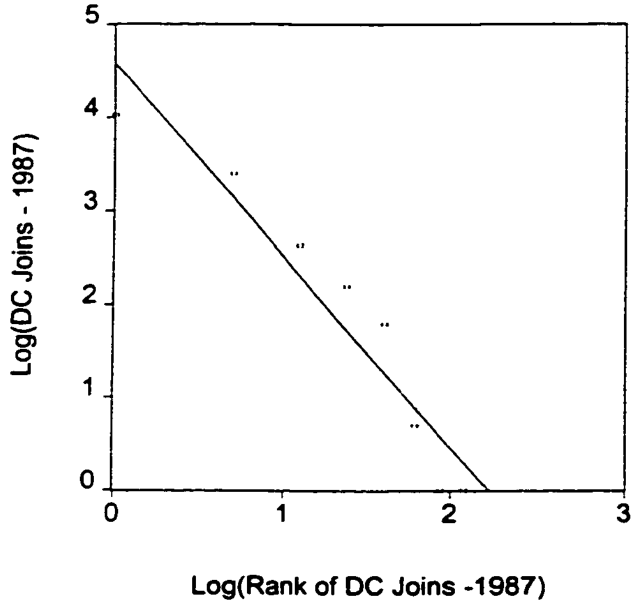

Table 6.8.

Intercept and Slope
DC Joins – 1987

Intercept	4.56 (11.72)
Slope	-2.05 (-7.78)
Adj. $R^2 = 0.93$ $N = 9$	

t-stat in parenthesis

Figure 6.11 The Rank-size Distribution Applied to DC Joins in 1997

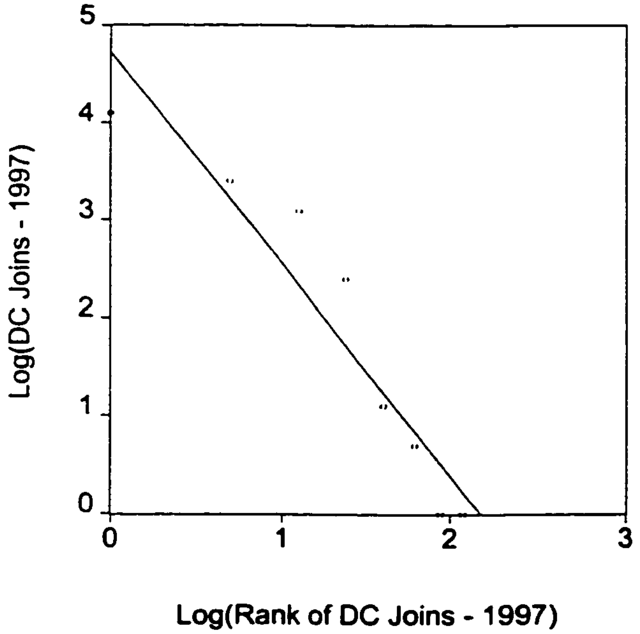

Table 6.9.

Intercept and Slope
DC Joins – 1997

Variable	1997
Intercept	4.72 (11.71)
Slope	-2.16 (-7.78)
Adj. $R^2 = 0.90$ $N = 9$	

t-stat in parenthesis

Heavy-Tail Distributions

Distributions with infinite variance are classified as 'heavy-tailed distributions'. Infinite variance implies that the probability of observing extreme values of a random variable X is greater than the probability of observing extreme values when the random variable is Gaussian distributed (De Vany et. al., 1999). In other words, heavy-tailed distributions have more mass located in the tails of their density functions. The tail index α measures the rate of decline of a distribution's density function slope. For heavy-tailed distributions, α is greater than zero and less than two.[17]

The growing missile capabilities of North Korea, Iran, and other nations have alarmed U.S. policymakers in recent years. Long-range missiles, once exclusively monopolized by a handful of countries, are now spreading throughout the world. Figure 1.4 (Chapter 1) shows that the missile ranges and payloads in the Middle East, Asia and Europe increased between 1987 and 1997.

The tail-indices have important implications for range and payload distribution. If for example, the range distribution exhibits heavy-tail characteristics, then the probability we observe missiles with extreme ranges, say ICBMs or perhaps infinite ranges a Space Launch Vehicles (SLVs), is greater than the would be the case if missile ranges were normally distributed. [18] Similarly, for payload distributions with infinite variance would

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[17] There are various methods for calculating the heavy-tail index (see Adler et.al. 1998). The slope estimated from the rank-size log-log plot is close approximation.

[18] Ballistic missiles share many overlapping technologies with satellite launcher vehicles or SLVs. The Soviet *R-7* SLV that lifted *Sputnik* and Yuri Gargarin into orbit, doubled as an intercontinental ballistic missile (ICBM) during the 1960s. Modifications to the *Atlas* ICBM made possible John Glenn's Earth orbit in 1962. Although the *R-7* and *Atlas* ICBMs were retired more than 35 years ago, they remain in production today as key SLVs for Russia and the United States. China's SLVs, the *CZ-1*, *CZ-2*, *CZ-3*, and *CZ-4*, are based on the *DF-4* or *DF-5* ICBM. Iraq, Israel, North Korea, and India have used their ballistic technology as a basis for building space launchers.

mean that we observe missiles with extreme payload yields (nuclear) more frequently than would be the case if the distributions were normal.

Table 6.10 shows the descriptive statistics for range and payload variable used in the regression analysis of Chapter 5. The standard deviation for both variables increases over time as the mean increases, however the range SDs are large.

Table 6.10

Missile Range and Payload Descriptive Statistics

Year	Missile Range (km)		Missile Payload (kg)	
	Mean	SD	Mean	SD
1967	309.57	728.93	639.12	277.47
1977	325.14	522.17	760.71	280.65
1987	564.96	832.11	775.80	339.03
1997	770.66	906.10	908.33	423.67
Overall	519.11	790.56	771.16	356.09

Notes. SD = Standard Deviation

While the SDs suggest the possibility of heavy-tail distribution for range and payload, these statistics are incomplete because they only include the *longest* range and *heaviest* payload missiles of a country's arsenal; the smaller size missile ranges and payloads are ignored.[19] In reality, armed nations typically have more than one type of ballistic missile. For instance, Iran had at least eight different types of ballistic missiles with various ranges and payloads in 1994.[20] The availability of data catalogued in the Nonproliferation Review (1994, pp. 183-186) permits us to empirically characterize the range and payload distributions for ballistic missiles of all sizes.[21]

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[19] The alternative would have been to use an average range and payload. However, an average range would understate a countries capability.

[20] Nonproliferation Review Spring/Summer 1994, p. 84-87

[21] This research is limited to missile ranges under 3,500 km (see Chapter 1). Longer range missiles such as ICBMs and SLBMs have not proliferated beyond a few states and are therefore not part of contemporary ballistic missile proliferation. However, this does not preclude the emergence of long-ran missiles from the complex interactions of the states considered.

The slope of the rank-size log-log range plot is an approximation of the tail index. A tail index of 1.66 indicates that the range distribution's second moments or variance is infinite. This implies that missile ranges vary substantially and cannot be fully understood by studying the mean of missile ranges. Conventional approaches to arms control disregard the underlying form and content of the statistical distribution. Heavy-tail range distribution implies that long-range missile development is volatile and uncertain. Volatility and uncertainty has certainly been the experience of the established powers: The US' first ballistic missile in 1950s Corporal was too complicated to be used on the battlefield. Its development was dismissed as a learning experience. Although the Soviet Union was the first nation to deploy an ICBM, several attempts were required to produce one that was fully acceptable for military use; China built and abandoned several ballistic missile prototypes before settling on the *DF- 2* intermediate range ballistic missile; Britain for reason still debated, announced its total commitment to missile development in 1957 and then gradually cancelled most of its projects by 1962. In 1991, France abandoned development of its *Hades* ballistic missile project after building just 30 missiles: The $5 billion French *S-45* IRBM with 4000km range was cancelled outright.

Missile programs in developing countries also face uncertainty. The widely held view that current missiles in Iran and North Korea will *inevitably* evolve into intercontinental ballistic missiles deserves greater scrutiny in light of this research. These countries are not only hampered by the technological hurdles of 'rocket science' they (unlike the established powers) face international sanctions against missile technology transfers.

Self-Similarity

The concept underlying self-organization is self-similarity. Self-similarity or invariance against changes in scale or size is an attribute of many laws of nature and innumerable phenomena in the physical world. Self-similarity is one of the decisive symmetries that shape the universe (Schroeder, 1991). Symmetry implies invariance against change: something stays the some despite potentially alterations. For example, Newton's law of gravity mirrors exact symmetry: there is no difference between left and right in the attraction of heavenly bodies.

A significant symmetry can be found in the invariance with respect to missile ranges. Figures 6.11 and 6.12 display the log-log scatter plots for missile ranges in the Middle East and North Africa (MENA) and Iran. Tables 6.9 and 6.10 shows that the slope and intercept for the MENA and Iran. Although the slopes and intercepts are significantly different distributions conform power law behavior. Moreover, the heavy-tail indices for the MENA and Iran are less than two and consistent with the heavy-tail indices for the entire sample. Missile ranges in the Middle East and Iran are volatile and uncertain.

Figure 6.12 The Rank-size Distribution Applied To Missile Ranges for MENA, 1994

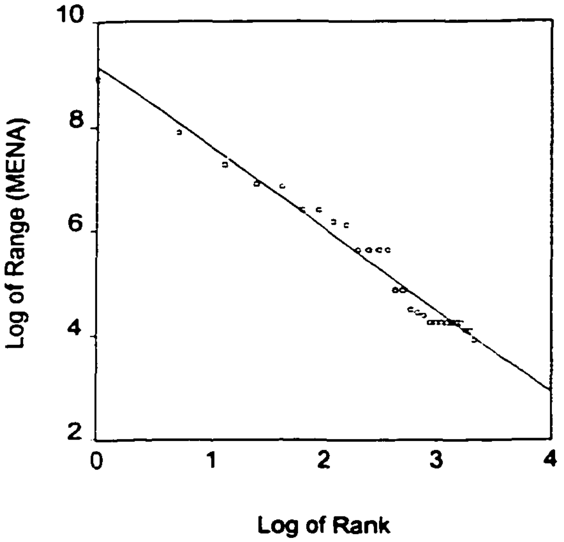

Table 6.11

Intercept and Slope
Range – MENA 1994

Intercept	9.14 (68.15)
Slope	-1.55 (-29.73)
Adj. $R^2 = 0.97$ $N = 28$	

t-stat in parenthesis

Figure 6.13 The Rank-size Distribution Applied To Missile Ranges in Iran, 1994

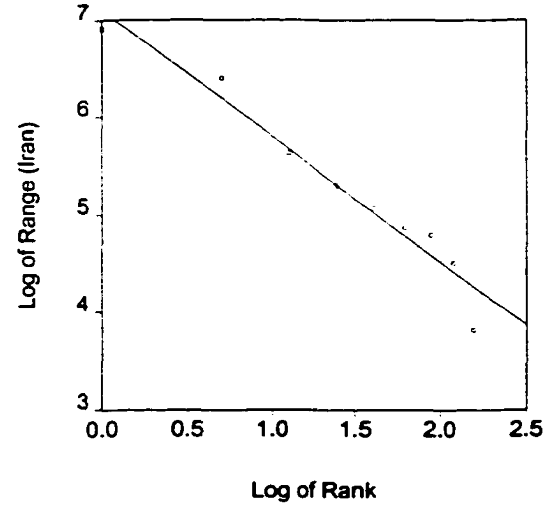

Table 6.12

Intercept and Slope
Range – Iran, 1994

Intercept	7.09 (41.54)
Slope	-1.29 (-11.93)
Adj. $R^2 = 0.95$ $N = 9$	

t-stat in parenthesis

Conclusion

Standard theories of arms racing explanation portray weapons proliferation and innovation as the product rational optimization. However, the notion of optimization may have no functional meaning if the search space is large. Alternatively, I propose a theory of ballistic missile proliferation based on the principles of self-organizing systems. In a self-organizing system, the order evident in the world – is emergent. Emergent order arises from the interaction among states. This order is not reducible from the actions of one or a few states. Ballistic missile proliferation is a consequence of competitive and adaptive behavior of states in the international system. Macro-level order emerges from the desire among states to enhance their security vis-à-vis neighboring states.

When outcomes emerge from many interactions, it may not be possible to determine the contribution of each taken separately. Because states are part of an international system, evaluating the merits of non-proliferation regimes is complicated. When institutions seek to restrain undesired behavior, the results are very often unintended. As Jervis points out: the problem is not enforcement *per se* but in a system "we can never do just one thing." For example, the missile technology control regime proponents believe that controlling missile technology exports will allow them the change the behavior as desired of some states. This would be the case if everything else remained constant. But in a system, everything else is not constant. Thus, we should not be surprised at some of the anomalous side effects of international attempts at regulating missile technology.

Missile regulations have altered the incentive and opportunities of several actors, and produced unintended consequences. Cut off from western missile technology, developing nations have found alternative sources for getting missile technology. Money that could no longer legally buy missiles from abroad went into developing domestic missile production. Missile exports have earned the North Korean economy with nearly $1 billion.[22] One cannot plausible conclude that all missile regulation is counter-productive but the complexity of interactions means that we cannot be certain that the proposed rules will work as intended, even after the fact.

This analysis suggests that local security issues primarily drive changes in missile range and payload parameters. These local effects *can* have macro-level results. Caution is advised in viewing these parametric changes as inevitable or deterministic. Ballistic missiles themselves are complex systems composed of many smaller interacting subsystems. Scaling up one particular component is impractical or meaningless without commensurate technological modifications to other related components. Accordingly, increasing a missile's range by adding on stages or enlarging existing fuel tanks must be accompanied with structural modifications that enable the vehicle to endure greater heat and vibrations generated from a longer flight. Thus, the tendency for the Iraqi *Al Hussein* missiles, a modified *Scud B* variant, to disintegrate upon re-entering the atmosphere has been attributed to engineering modifications that overlooked the increase moments (about the vehicle center of gravity) generated by the heavier strap on boosters. These moments exerted forces that degraded the missile's structural integrity.

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[22] According to testimony to Deputy Assistant Secretary Eihorn, North Korea missile exports have "earned almost $1 billion dollar over the past decade." *The Proliferation Primer: A Majority Report of the*

Areas of Future Research

Some complex systems autonomously evolve from a large region of state space to a smaller state space. The smaller region is known as an attractor. An attractor is the preferred position of a complex system, such that if is started from another state, it will evolve until it arrives at the attractor and will stay there in the absence of other factors. The center of a fishbowl containing a ball or planetary orbits are examples of attractors-they all specify a restricted volume of a state space. The larger area of the state space that leads to an attractor is called its basin of attraction and contains all of the possible trajectories to the attractor. Some complex systems preferred position is an infinite sequence-called a strange attractor.

An area of future research might be to determine if the cellular automaton lattices, considered here, evolve into attractors. One way of measuring an attractor would be to take say 1,000 random initial conditions and counting the number of distinct final states to which they evolve. If the number of final states is significantly smaller than the number of initial states, then you have multiple attractors, each with a basin of attraction. Conversely, if the number of final states is comparable to the number of initial states, this is probably not an attractor. The final configuration of the lattice structures in the experiments of Chapter 2 is an attractor.

Another area for potential research related to arms control and disarmament, might be to see how the steady-state lattice system reacts to random shocks. This could involve randomly disarming 20 sites and/ or changing the status of five randomly selected sites and allowing the system to evolve again to steady state.

Subcommittee on International Security, Proliferation and Federal Services (1998, p. 33).

Although ballistic missile proliferation is the focus of this research, there is an opportunity to generalize to results to human interactions and behavior. Self-organization arises "specifically out of diversity of goals, motives, and aspirations over the course of sociohistorical evolution that ... spontaneous order and the socioeconomic pattern on which it is based, is gradually formed" Ruzavin (1994, p. 72). Future empirical research might consider how similar self-organization might be applied to the complexity of international relations.

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Appendix A: Missile Range, Payload Deployment and Testing

Table 1A. Missile Ranges, Payloads, Country and Year Deployed/Tested

Missile	**Range (km)**	**Payload (kg)**	**Country (Year Deployed)**
Honest John	40	550	USA (1954)
			Greece (1959)
			S. Korea (1959)
			Italy (1960)
			Turkey (1960)
			Britain (1960)
			Taiwan (1961)
			France (1962)
			W. Germany (1964)
			Denmark (1967)
			Italy (1967)
			Netherlands (1967)
Sergeant	NA	NA	W. Germany (1964)
			France (1967)
Pluton	120	400	France (1974)
Lance	120	450	USA (1973)
			Israel (1976)
			Turkey (1978)
			Belgium (1978)
			W. Germany (1978)
			Italy (1979)
			Netherlands (1979)
Pershing I	450	1000	USA (1967)
			W. Germany (1967)
Pershing II	1800	1500	USA (1979)
			W. Germany (1983)
Hades	480	400	France (1980)
Scud-B	300	1000	USSR (1965)
			Czech (1970)
			E. Germany (1970)
			Poland (1970)
			Romania (1972)
			Hungary (1973)
			Egypt (1973)
			Syria (1974)
			Iraq (1974)
			N. Korea (1976)
			Libya (1978)
			S. Yemen (1979)
			Iran (1985)
			Afghanistan (1989)
			Ukraine (1992)
			Russia (1992)
			Czech Rep. (1992)
			Slovakia (1993)
			Armenia (1994)
			Turkmenistan (1997)
Scud-C	500	500	Iran (1988)

SS-21	70	480	USSR
			Syria (1983)
			E. Germany (1987)
			Czech (1987)
			N. Yemen (1988)
			Bosnia (1996)
			Ubekestan (1997)
SS-23	500	NA	USSR (1986)
			Bulgaria (1990)
			E. Germany (1990)
Scaleboard	900	NA	USSR (1978)
Taepo Dong	4000	2000	North Korea (1998)
Al Hussein	650	500	Iraq (1988)
Al Abbas	900	300	Iraq (1988)
Saqr-80	80	450	Egypt (1992)
Jericho I	500	680	Israel (1967)
Jericho II	1500		Israel (1987)
CSS2	2700	1500	China (1964)
			S. Arabia (1988)
FROG-3,-4,-5	40	NA	USSR (1957)
			Cuba (1960)
			Egypt (1968)
			Algeria (1974)
FROG-7	70	1000	USSR (1967)
			N. Korea (1970)
			Bulgaria (1970)
			Czech (1970)
			Cuba (1970)
			E. Germany (1970)
			Hungary (1970)
			Poland (1970)
			Egypt (1971)
			Bulgaria (1973)
			Syria (1973)
			S. Yemen (1979)
			Khazakstan (1992)
			Belarus (1992)
			Turkmenistan (1997)
Haft-I	80	1100	Pakistan(1991)
Haft-II	300	1100	Pakistan (1993)
Haft III	600	500	Pakistan (1993)
Ghauri	1250	1500	Pakistan (1998)
Shaheen	750	1000	Pakistan (1999)
Ghauri II (Haft V)	2300	2200	Pakistan (1999)
Prithvi	150	1000	India (1988)
Agni	2200	2000	India (1989)
Agni II	2500	2000	India (1999)
M-9	600	500	China (1987)
M-11	300	500	China (1986)
			Pakistan (1996)
NHK-1	250	NA	South Korea (1988)
Ching Feng	130	400	Taiwan (1983)
Iran-130	130	500	Iran (1988)
No Dong I	1000	1000	N. Korea (1993)
No Dong II	1500	1000	N. Korea (1995)
Scud C	500	1000	N. Korea (1992)

Condor I	150	400	Argentina (1985)
MB/EE 150	150	500	Brazil (1986)
MB/EE 350	350	NA	Brazil (1986)
SS-300	300	1000	Brazil (1986)
Nazeat-6	105	850	Iran (1987)
Nazeat-10	140	250	Iran (1988)
Oghab	34	70	Iran (1988)
Shahab-3	1300	700	Iran (1998)
Shahab-4	2000	1000	Iran (1998)
Arniston	1450	NA	S. Africa (1989)

Sources: Listed below in Data Sources.

Appendix B: Data Sources

Y: The International Institute for Strategic Studies (IISS), annually compiles estimates military hardware by country in The Military Balance. Information on the countries with tactical ballistic missiles is categorized under "SSM" or surface-to-surface missiles. *The Military Balance*, gives the number and type (name) of tactical missiles or launchers.

SAM: The Military Balance (IISS/ London) also compiles annual documentation of nations with surface to air missiles or SAMs.

Payload: Missile payload range are taken from the following sources: Arms Control and Disarmament Agency, World Military Expenditures and Arms Transfers, 1988 (1989); Karp (1996, Appendix 1); Navias (1993, p. 33); Nolan (1993, Table 4-2); Missile and Space Launch Capability of Selected Countries. The Nonproliferation Review Spring-Summer 1996, pp. 162-165.

Borders and Area: The World Factbook, prepared annually by the Central Intelligence Agency (CIA) publishes geographic data for countries. Information was provided by : the American Geophysical Union, Bureau of the Census, Central Intelligence Agency, Defense Intelligence Agency, Defense Nuclear Agency, Department of State, Foreign Broadcast Information Service, Maritime Administration, National Imagery and Mapping Agency, National Maritime Intelligence Center, National Science Foundation (Antarctic Sciences Section), Office of Insular Affairs, US Board on Geographic Names, US Coast Guard, and other public and private sources. This data is online at:

http://www.odci.gov/cia/publications/factbook/. Geo-political data for earlier periods is available from yearly publications of Funk and Wagnall's The World Almanac and Fact Book.

NORMS: Data for GNP the International Financial Statistics of the International Monetary Fund and the World Tables of the World Bank.

Milex:
World Military Expenditures and Arms Transfers Annual Reports. U.S. Arms Control and Disarmament Agency. Washington, DC.: U.S. Government Printing Office. Statistical notes detailing the calculation of the Milex, military expenditures as a percent of central government expenditures are available in World Military Expenditures and Arms Transfers: 1967-1976, pp. 20 –21; World Military Expenditures and Arms Transfers: 1985, pp. 16-19.

MTCR Membership: Appendix A in The International Missile Bazaar: The New Supplier's Network, list acceding member countries of the MTCR from 1987 – 1993. Deborah Ozag of the International Missile Proliferation Project at the Monterey Institute of International Studies (miis.edu) list acceding member countries from 1994 to the present. U.S. Arms Control and Disarmament Agency. (1997). Missile technology control regime marks 10th anniversary. http://www.acda.gov/factshee/exptcon.

Table A2 List of Countries Sampled

Afghanistan Albania Angola Argentina Algeria	Barbados Belarus* Belgium Benin Belize	Britain Bulgaria Burma Burundi Cameroon	Colombia Congo Costa Rica Croatia Cuba*
Austria Azerbaijan* Bahrain Bahamas Bangladesh	Bhutan Bosnia* Bolivia Botswana Brazil	Canada Central African Rep. Chad Chile China	Czechoslovakia Czech Republic* Denmark Dominican Rep. Equator
East Germany Egypt El Salvador Estonia Ethiopia	Finland France West Germany Germany* Greece	Guatemala Guyana Haiti Honduras Hungary	India Indonesia Iran Iraq Ireland
Israel Italy Jamaica Japan Jordan	Kuwaiti Kyrgystan Laos Lebanon Liberia	Libya Luxembourg Lithuania* Macedonia* Malaysia	Mali Mauritania Mexico Moldavia Mongolia
Morocco Mozambique* North Korea North Yemen Nepal	Netherlands Nicaragua Niger Nigeria Norway	Oman Pakistan Panama Papa New Guinea Paraguay	Peru Poland Portugal Qatar Romania
Rwanda South Korea South Yemen Saudi Arabia Senegal	Sierre Leon Singapore Slovakia* Spain Sri Lanka	Sudan Sweden Switzerland Syria Tanzania	Taiwan Tajikistan Thailand Togo Tunisia
Turkey Turkmenistan* Ukraine* USA Uruguay	USSR* Uzbekistan* Vietnam South Vietnam* Venezuela	Yugoslavia Zaire Zambia Zimbabwe Kazakhstan*	Russia*

Notes. Asterisk (*) indicates new country

Appendix C: Open and Periodic Boundary Conditions

I use one-dimensional (1-D) lattice (see Figure A1) to explain open boundary conditions. A one-dimensional CA consists of a line of sites. If it is infinitely long the boundaries (i.e. the two endpoints of the line) are at infinity that means practically there are no boundaries and I am therefore unconcerned with them. Here two extra sites are added to the lattice, one to the left of site 1 and the other to the right of site 9 in the following way:

Figure A1 Open Boundary Conditions: 1-D Cellular Automata

o----o----o----o----o----o----o----o----o----o----o

0 (1) (2) (3) (4) (5) (6) (7) (8) (9) 10

The boundary sites are labeled 0 and 10 respectively. The value of the CA is at sites 0 and 10 are always maintained at 0 which means whatever these sites get from interacting with the interior sites are disposed off as though they are infinite sinks. For the two-dimensional (2-D) case shown in Figure A2, 40 additional sites labeled 0 though ten are added to the lattice perimeter and maintained at zero.

Figure A2. Open Boundary Conditions: 2-D Cellular Automata

	0	1	2	3	4	5	6	7	8	9	10
A	0	0	0	0	0	0	0	0	0	0	0
B	0	C	C	C	C	C	C	C	C	C	0
C	0	C	C	C	C	C	C	C	C	C	0
D	0	C	C	C	C	C	C	C	C	C	0
E	0	C	C	C	C	C	C	C	C	C	0
F	0	C	C	C	C	C	C	C	C	C	0
G	0	C	C	C	C	C	C	C	C	C	0
H	0	C	C	C	C	C	C	C	C	C	0
I	0	C	C	C	C	C	C	C	C	C	0
J	0	0	0	0	0	0	0	0	0	0	0

Periodic Boundary Conditions

Imposing periodic boundary conditions on a finite lattice is done by equating (at each time-step) the site strategies in column 9 to those in column 0 and equating the site strategies of column 1 to those in column 10 (see Figure II). Similarly, the strategies of row J are equated to the strategies of row A and the strategies of row K are equated to the strategies of row B.

Figure A2. Periodic Boundary Conditions

	0	1	2	3	4	5	6	7	8	9	10
A	C	C	C	C	C	C	C	C	C	C	C
B	C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	C	C	C
D	C	C	C	C	C	C	C	C	C	C	C
E	C	C	C	C	C	C	C	C	C	C	C
F	C	C	C	C	C	C	C	C	C	C	C
G	C	C	C	C	C	C	C	C	C	C	C
H	C	C	C	C	C	C	C	C	C	C	C
I	C	C	C	C	C	C	C	C	C	C	C
J	C	C	C	C	C	C	C	C	C	C	C

Appendix D: C-Programming Code

```
 /*
 *
 *      Ballistic Missile Proliferation/ Payload Simulation Model
 *                      by
 *                  Daniel T. Barkley
 *             Self-Organizing Payload Model
 *
 *      Last Changed: JAN. 23, 2000
      Von Neumann Neighborhood;
      Missile Payload
      Factors: -1 0 4 6 8
      Initial Seeding: 90: -r and 10: +r
      Open Boundary Conditions
 *    Random Numbers: 99 10 113 793 3924 777
 *
#include <stdio.h>
#include <stdlib.h>
#include <ctype.h>

/* Defines the width x height of the arrays used.*/
#define LIFE_GRID 10

/* Defines the number of generations the program should simulate. */
#define N 20

/* Function to setup initial generation. */
void load_init(int [LIFE_GRID+2][LIFE_GRID+2]);

/* Function to move forward one generation. */
void step_generation(int [LIFE_GRID+2][LIFE_GRID+2]);

void print_grid(int [LIFE_GRID+2][LIFE_GRID+2]);
/* Function to print the array. */

int neighbors(int [LIFE_GRID+2][LIFE_GRID+2],int,int);
/* Function to count the number of neighbors for a given cell. */

void copy_array(int [LIFE_GRID+2][LIFE_GRID+2], int
[LIFE_GRID+2][LIFE_GRID+2]);
/* Function to copy the contents of one array to another. */

void main(void)
{
        int life[LIFE_GRID+2][LIFE_GRID+2];
/* Array used for the simulation. */
        int i;
        unsigned int seed;
/* Holds the user entered seed for the random number generater. */

/* Get a unsigned int from the user and use it to seed the random
number
generator. */
```

```
        printf("\nPlease enter a postive integer: ");
        scanf("%u",&seed);
        srand(seed);

/* Print a message to the screen and run load_init to setup the initial
generation. */

        printf("\n\nGenerating inital grid...\n");
        load_init(life);

        /* Loop to cycle through the different generations. */
        for (i=1;i <= N;i++)
        {
                printf("\nGeneration: %i\n\n",i);
/* Print the generation number on the screen. */
                print_grid(life);
/* Call print_grid to display the contents of the array. */
                step_generation(life);
/* Call step_generation to generate the next generation. */
        }
}

/*
 *      load_init() is passed the address of an array of characters.
It
      moves through
 *      each cell in the array, based on a random number provided by
the
      rand() function
 *      it randomly places a missile range (0-100) or a zero in the
given
      cell of the array.
 */

void load_init(int A[LIFE_GRID+2][LIFE_GRID+2])
{
    int y,x,z,r;
        for (y=0;y < LIFE_GRID +1;y++)
        {
                for (x=0;x < LIFE_GRID+1;x++)
                {
                        z=(int)(100.0*rand()/RAND_MAX+1.0);
            /*Generates a random number between 0 and 10. */

                  r=(int)(10.0*rand()/RAND_MAX+1.0);

            /*Generates a random range between 0 and 100. */

                          if (z > 90)

                               A[y][x]= r;
                        else
                                A[y][x]= -r;
                }
        }

}
```

```
/*
 *      step_generation() is passed the address of an array of
characters.
      It also sets
 *      up an array of the exact same size as the one whose address was
      passed.  The
 *      function moves through each cell in the array, calling
neighbors()
      to get
 *      the number of neighbors the current cell has.  Based on the
data
      from neighbors()
 *      and the rules of Life, it either places a * or space in the
      corresponding cell
 *      of the second array.  Once the function has finished, it calls
      copy_array() to
 *      copy the contents of the second array into the first array.
 */

void step_generation(int A[LIFE_GRID+2][LIFE_GRID+2])
{
        int i,j,x,p,l,q;
            int Z[LIFE_GRID+2][LIFE_GRID+2];
/* Defines a second array of the same size as the one being passed. */

        for (i=0;i < LIFE_GRID+1;i++)
        {
                for (j=0;j < LIFE_GRID+1;j++)
                {
                    x=neighbors(A,i,j);

/* Call neighbors() to see how many neighbors w/ missiles this cell has
*/
                  q=(int)(10.0*rand()/RAND_MAX+1.0);
                /*Generates a random number between 0 and 10. */
                      if ((A[i][j] >= 0) || (A[i][j] < 0))

                     /* When the country is unarmed or armed */
                {
                              if ((x == 0))
                          {
                          p=q;
                          Z[i][j]= A[i][j]-p;
                          }

                        else if ((x == 1) && (A[i][j] < 0))
                          {
                          p = A[i][j];
                          Z[i][j]=p;
                          }

                                 else if ((x == 1) && (A[i][j]>= 0 ))
                                   {
                                   p = A[i][j];
                                   Z[i][j]=p;
                                   }
```

```
                                        else if ((x == 2))
                                   {
                                          Z[i][j]=A[i][j]+ 4*q;
                                   }

                                        else if ((x== 3))
                                   {
                                   p = A[i][j] + 6*q;
                                          Z[i][j]=p;
                                   }

                              else if (x > 3)
                                   {
                                   p = A[i][j] + 8*q;
                                   Z[i][j]=p;
                                   }

                         else
                              Z[i][j] =0;

                         }
                      }
          }

          copy_array(Z,A);  /* Copy the contents of array Z to array A.
*/
}

/*
 *        print_grid() is passed the address of an array of characters.
It
      moves through this
 *        array printing each charter to the display.  It also prints
cell
      numbers across the
 *        top, and along the left side of the output.
 */

void print_grid(int A[LIFE_GRID+2][LIFE_GRID+2])
{
          int y,x;
          int command;


          /* Print column numbers left to right. */
          printf("  ");
          for (x=0;x < LIFE_GRID+1;x++)
              printf("%4d ",x);
          printf("\n\n");

          /* Print a row number and the contens of that row. */
          for (y=0;y < LIFE_GRID+1;y++)
          {
                  printf("%i ",y);
                  for (x=0;x < LIFE_GRID+1;x++)
                  {
```

```
                        printf("%4d ",A[y][x]);
                }
                printf("\n");
        }
printf("Press enter to continue");
command = getchar();

}

/*
 *      neighbors() is passed the address of an array of characters,
and
      two integers.  It checks
 *      the positions above, below, to the left & right, and diagnly
from
      the cell specified by
 *      the two itegers passed to the function.  For each of the cells
      checked, ones that contain
 *      a * cause 1 to be added to the sum variable.  When finished the
      function has calculated
 *      the number of neighbors for the given cell in the given array.
It
      return this value to
 *      the calling function.
 */

int neighbors(int A[LIFE_GRID+2][LIFE_GRID+2],int y,int x)
{
      int sum=0,i;
        int v,w;

      for (v=0;v < LIFE_GRID+1;v++)
        {
            for (w=0;w < LIFE_GRID+1;w++)
            {

      if ((v == 0) || (w == 0) || (v == LIFE_GRID) || (w == LIFE_GRID))
        {
      A[v][w]= A[v][w];
      }

 }}
/* Check for missiles to the left. */
        if ((x-1) >= 0)
        {
                if (A[y][x-1] > 0)
                        sum+=1;
        }

/* Check for missiles to the right,*/
        if ((x+1) < (LIFE_GRID+1))
        {
                if (A[y][x+1] > 0)
                        sum+=1;
      }
        /* Check for missiles above the cell. */
        if ((y-1) >= 0)
```

```
        {
                if (A[y-1][x] >= 0)
                        sum+=1;
        }


        /* Check for missiles below the cell. */
        if ((y+1) < LIFE_GRID+1)
        {
                if (A[y+1][x] > 0)
                        sum+=1;
      }


/* Return the number of neighbors found to the calling function. */
      return sum;
}

/*
 *      copy_array() is passed the address of two character arrays.  It
      makes an exact
 *      copy of the contents of the first array, placing the copy in
the
      second array.
 */

void copy_array(int A[LIFE_GRID+2][LIFE_GRID+2],int
B[LIFE_GRID+2][LIFE_GRID+2])
{
        int y,x;

        for (y=0;y < LIFE_GRID+1;y++)
                for (x=0;x < LIFE_GRID+1;x++)
                        B[y][x]=A[y][x];
}
```