Arms Racing, Coercion and War

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Abstract – English

This paper constructs a graphical and mathematical model of dyadic interstate security competition. It does so by integrating arms racing and war initiation in to a single rational choice framework. The model is constructed from rigorously-defined concepts and all assumptions are made explicit. Equilibrium values for security-based arms racing are derived under the model and compared to conquest-seeking arms races. Comparative static results are provided for several shocks to the basic system. The model is informally extended in to probabilistic war scenarios. Finally, a number of testable predictions generated by the model are presented.

Abstract – French

Ce mémoire présente un modèle graphique et mathématique du conflit dyadique dans le domaine de la sécurité internationale. Le modèle permet d'interpréter la course aux armements et le déclenchement des guerres dans un cadre formel. Le modèle est construit a partir de concepts rigoureusement définies et nos postulats ont été présenté de manières explicites. Les valeurs d'équilibre pour une course aux armements voulant assurer la sécurité nationale sont prédits à partir du modèle et comparé aux valeurs produites pour une course aux armements avec des objectifs de conquête. Différents résultats d'analyse statique sont comparés pour différentes perturbations du modèle de base. Le modèle est étendu intuitivement pour présenter des scénarios probabilistes de guerre. Finalement, de nombreuses propositions réfutables sont dérivées du modèle.

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Introduction

Inter-state conflict is well-studied but not well-theorized. Centuries of political practice have raised more questions than accumulated scholarship has answered. As a result, important gaps in the field of international relations theory exist for arms racing, war initiation, and war termination. Even widely-accepted indicators of "power" fail to outperform coin flips in predicting which state will emerge victorious from a given war (Biddle 2004: 7). One of the more prominent trends in the post-World War 2 study of international conflict is the use of rational choice theory. From a rational choice perspective, state behaviour should exhibit predictable regularities, as states facing similar circumstances are expected to make similar decisions. This begs the question that if state behaviour is rational, then why is it so difficult to predict? One part of the answer may be that while arms racing and war initiation are interrelated phenomena (arms racing is meaningless without the threat of war, and wars are fought with weapons stocks that are largely accumulated in peacetime), they have traditionally been studied separately.

This paper will construct an integrated model of inter-state conflict, beginning with arms races and continuing to war initiation, allowing the investigation of both areas simultaneously. A comprehensive model of this kind differs fundamentally from past approaches and should lead to new (and more accurate) insights. Furthermore, by constructing a relatively simple mathematical model, rigorous hypothesis testing can be performed, providing strong evidence for or against the model and its assumptions.

Given the inherently deductive nature of mathematical model-building, it is crucial to establish as far as possible the truth of foundational assumptions and the utility of primitive notions.[1] Thus the paper will first establish the epistemological

[1] Primitive notions are axioms, concepts and terms which remain undefined within the formal model itself and whose existence is considered either self-evident or analytically necessary. Lines, points and angles are primitive notions of geometry, for example.

framework of model-building in the social sciences, drawing on the methodology of economics and the principles of formal logic. Next it will survey the literature on arms racing, war initiation, and other relevant domains in order to assess which assumptions are reasonable and which stylized facts[1] the model should be expected to predict. Next, the model's components and assumptions are made explicit and used to derive theories of arms racing and war initiation. Predictions are then derived from this model for heuristic purposes. The model is then progressively expanded by relaxing core assumptions, thereby improving the accuracy of its predictions. At all times, the aim of the model construction process will be to maintain logical consistency and clarity of exposition. In following the deductive approach, this paper addresses the most difficult issues first, and devotes much of its argumentation to establishing the validity and clarity of its assumptions and concepts. Once the logical foundation of the model is in place, its conclusions flow easily from that point onwards.

I. Analytical Priors

1.1 Social Science Theories

What is a theory?

For the purposes of this paper, the term "theory" will be used in its most basic, inclusive and "pure" sense, one which is derived from the natural sciences and ultimately mathematics (e.g. Machover, 1996). A theory is any set of assumptions, plus all of the logical implications which are derivable from that set.[2]

This usage corrects a tendency among some political scientists to define "theory" in ways which are idiosyncratic to the social sciences or which place arbitrary restrictions on what theories may or may not do (e.g. King, Keohane and Verba

[1] Stylized facts are empirical generalizations which, although not true in all cases or at all times, are consistent enough to be used for theoretical and heuristic purposes.
[2] Under this usage, for example, it is correct to speak of Waltz's (1979) theory of structural realism, but "deterrence theory" is a misnomer, as there are many such "theories."

1994). Instead, this definition focuses our attention on the essential elements of theories, and thus covers the widest possible range while avoiding "conceptual stretching." (Sartori 1984) It covers descriptive theories generated by crisis researchers (Brecher 2000), deductive game theory models, inductively-generated theories such as democratic peace theory, general theories of international (e.g. Holsti, 1988) or domestic politics (e.g. Huntington 1968), as well as explanations for specific events such as the Cuban Missile Crisis (Allison 1971) or theories of single issue-areas (Paul 2000). Each of these topics has attracted considerable attention from scholars, and there seems to be no reason to designate an arbitrary subset as "atheoretical." What unifies each of the theories listed above is not their purpose, approach or subject matter, but rather their common epistemological structure.

The role of theories

Why formulate theories? This paper asserts that theories and theory-making are ultimately intended to be useful. Without delving in to the specifics of the term, it seems intuitive that theories are useful to the extent that they are true (leaving aside the special case of Plato's "noble lie" (Plato 2007). Of course, "absolute truth" may be inaccessible to researchers, in which case theories can only approximate the truth[1] and thus many believe that this renders truth-seeking a futile activity. Yet even approximations of reality may bring considerable benefits. As Werner (1960) observed, the "unreasonable effectiveness" of theoretical physics is witnessed by the existence of machines which can exploit scientific principles repeatedly and upon command. Likewise, the imprecise laws of biology and medicine (which are "proven" using statistical techniques familiar to most social scientists) have still increased life expectancy by over a decade in OECD countries since 1960 (World Development Indicators Online). It is thus difficult to argue that the inherent incompleteness of theories renders theorizing a useless activity.

[1] This is the dominant view for philosophers of science (Popper 1957) as well as social science methodologists (e.g. Almond and Genco 1977).

One can also speak of the relevance, or lack thereof, of the research questions considered by scholars. For example: is war more likely in a bipolar or multipolar system? It is certainly an interesting question, and it is even perhaps an answerable one, given time and an uncanny degree of consensual thinking among political scientists. But is it a *relevant* question for decision makers? The answer here is clearly no. The United States will not scale back its global presence if research finds multipolar systems to be the most stable configuration of power. Nor will the European Union militarize its foreign policy simply because scholars claim that a bipolar world would be a happier one.[1] This issue is not considered further in this paper, but it is an important question for the discipline to consider.

One of the valid objections to invoking truth as a fundamental notion is the surprising vagueness of the philosophical concept of “truth” (Machover, 1996). We can infer, however, that the truthfulness of a theory is proportional to the accuracy of its predictions. A possible objection here is that truth cannot be measured absolutely (i.e. “This theory is three quarters truth, one quarter falsehood”) nor easily compared between domains (“Physics is twice as true as biology”). Following the example of welfare economists, we can dispense with cardinal or absolute measures in favour of ordinal ones, which permits only comparisons of two similar theories. This criterion precludes comparing theories from different domains of inquiry (as in the biology-physics example above) and allows for varying levels of historical development in different fields (deterrence theory started nearly from scratch with the publication of Bernard Brodie’s (1946) *The Absolute Weapon*). Thus neither case undermines the fundamental point at stake, namely that one theory is to be judged more truthful than another if its predictions are more accurate. And since predictions are typically domain-specific (with the recent exception of studies on genetics and voting by Fowler, Baker and

[1] **Error! Main Document Only.**Or, to take the ultimate example of policy irrelevance: legislators will find nothing of interest in papers which purport to predict their voting behaviour. They themselves have perfect foreknowledge of these events, and are unlikely to take solace in being told that their choice was contingent on, say, the heterogeneity of their constituency (Bullock III and Brady, 1983).

Dawes 2008), the accuracy criterion guarantees that valid comparisons can be drawn by focussing our attention not on the *level* of predictive accuracy, but rather on differences in levels of accuracy between two theories.

The importance of prediction

Yogi Berra once said: "It's tough to make predictions, particularly about the future." This statement may seem vacuous, but predictions can take many forms. And indeed empirical papers in political science typically attempt to predict events retrospectively. Of course, the most important and impressive form of prediction applies to events which have not yet occurred, or from a statistical standpoint, "out of sample" prediction (King 1991: 1049). The concept of prediction is also boarder than the way in which many political scientists use the term. When Waltz declared "Theories of evolution, after all, predict nothing in particular" (1997: 916) he displayed a profound misunderstanding of evolutionary theory, which predicts patterns in fossil location, genetic similarities between species, the rate of genetic divergence between isolated populations, the purposefulness of biological attributes , etc. Most of these are predictions about the past (i.e. fossils of a certain kind should be found at a certain depth in the earth, and should not diverge too greatly from those found deeper still), but even the theory of evolution makes future predictions about how micropopulations of a species should evolve. Other forms of prediction include the exclusion of certain phenomena as impossible (negative predictions), asserting a relationship between two or more variables (smoking will be related to future cancer development) and predictions about the time order of related phenomena (the inflation rate moves in the same direction as GDP growth, but lags such changes by several months).[1]

Predictions are critical to the usefulness of a theory because they allow control over the phenomena in question (Wigner 1960). This appeals directly to our concern with usefulness. If a phenomena is controllable by human agency (such

[1] Predictions are not guaranteed to be testable on demand by scientists. Astronomers, for example, must rely on ingenuity and natural events to supply data, as they cannot directly manipulate the objects which they study.

as the internal combustion engine or voter turnout), then the first step in such control is always to understand the object of study. Such understanding cannot exist in the absence of prediction, since if our predictions are constantly falsified, this suggests that our understanding is limited at best. On the other hand, if the phenomena is not susceptible to human agency (such as astronomical events), adaptation to the phenomena will require that as a first step that we be able to anticipate it. In either case, other theoretical attributes such as "explanatory power", parsimony or wide scope of study are irrelevant in the absence of high predictive accuracy. The ultimate test of any theory's usefulness is its relevance to a lay person outside the discipline. Such a person is unlikely to be interested in any inaccurate theory.

The importance of assumptions

Social scientists often emphasize the importance of "simplifying assumptions" in deriving their predictions (e.g. Friedman 1953; Waltz 1997; Keohane and Nye 2000). Yet this greatly understates the role that assumptions play in generating predictions - without assumptions it is impossible to make any predictions at all. Even simple supply and demand models require the *ceteris paribus* assumption to make the "trivial" prediction that a shortage of goods will increase prices. The necessity of assumptions follows immediately from the definition of prediction given above, but can also be argued on intuitive grounds. After all, even predictions that are not grounded in a (possibly implicit) set of assumptions may be expressed as the tautology A→A or "A, therefore A." An example is Zipf's (1935) law, which consists solely of the observation that the frequency of a word's use is inversely proportional to its ranking (thus the second most popular word will be used half as often as the first, the third will be used one third as often, etc). This law is precisely (and only) an assumption about the functional form of word-use frequencies.

Milton Friedman (1953) advanced three roles that assumptions played in social science. The first, prediction, is outlined above. The second is parsimonious presentation of a theory (compare the lengths of papers written by analytical and continental philosophers on the same topic). The third is specifying of the "conditions under which a theory is expected to hold." According to Friedman, these boundaries are determined in part by the use to which a theory is put. To use his example, the "assumption" of a vacuum in the law of falling bodies suggests that it will have limited real world applicability to air-resistant objects such as feathers. This view can be contrasted with more recent social science practice of specifying scope conditions in advance (Foschi 1997; George and Bennett 2005: 116-119; Levy 2004: 37). These are interesting questions, but their resolution is not central to the goals of this paper, and we can thus remain agnostic on such matters.

A final and important issue raised by Friedman is whether a theory should be judged by the realism of its assumptions or by the accuracy of its predictions. This paper takes predictive accuracy as the most important criterion, but it is worth noting that there is often a relationship between the two and that it is valuable to identify the plausibility of assumptions for the purposes of theory improvement. If A and B jointly imply C, yet C fails to materialize, which assumption(s) should be discarded? Pure logic provides no answer to this dilemma, but careful examination of a theory's assumptions may allow researchers to identify the most likely source of inaccuracy.

Evaluating theories

In studying most important research topics, social scientists are presented with an embarrassment of theoretical riches. Methodologists and philosophers of science have thus proposed a number of criteria by which theories should be evaluated against each other. These attributes vary, but a list of core criteria has emerged: predictive accuracy, falsifiability, consistency, parsimony, explanatory power, scope (sometimes labelled generality or generalizability) and cumulativity (e.g. Popper 1959: *passim*; Manheim, Rich and Willnet 2002: 20-22; Shoemaker, Tankard and Lasora 2003: 171; Bryman 2008: 19; Babbie 2006).

One problem shared by most of these catalogues is that criteria are *listed*, but not *ordered*. Thus they provide little guidance for deciding among tradeoffs between parsimony and prediction, or between scope and explanatory power. For the reasons advanced in section 1.1.3.1, this paper adopts prediction as the most important function of a theory, and thus all other attributes may be sacrificed in pursuit of higher predictive accuracy. It is possible that at very high levels of accuracy, the marginal benefits (in terms of usefulness) from improved prediction may be outweighed by the marginal costs of other theoretical attributes. Richardson (1960: 17) somewhat naively declared that once arms race prediction models had reached 98% accuracy, different criteria could be used to evaluate them. Needless to say, social science is far from such a threshold and this paper will proceed on the basis that prediction remains the overriding concern of social science theories.

In one sense, placing prediction first allows us to dispense with the ranking of other theoretical attributes, but these theoretical properties should not be ignored. The remainder of this section will show that other theoretical criteria are either supportive of prediction (falsifiability), implicit within a focus on prediction (consistency), or necessarily subordinate to it (parsimony, explanatory power, scope, cumulativity). It does *not* argue that the latter four conditions are undesirable, merely that they are less important relative to predictive accuracy.

Falsifiability, as advanced by Karl Popper (1959) is the criteria which delineates sciences from "metaphysics" on one side and mathematics on the other. A theory is falsifiable if and only if "it can be refuted by [empirical] experience" (Popper 1959: 41). Thus the model must both make predictions and define these predictions in terms of observable, real world outcomes. In economics, real business cycle models (e.g. King and Rebelo 2000) predict that spontaneous economic adjustments lead to optimal economic outcomes at all stages of the business cycle. Thus the economy is constantly in the "best of all possible worlds." Yet such an optimality prediction is not directly testable, as we cannot observe the best of all possible worlds, so instead real business cycle models are evaluated using their predictions about interest rates, labour markets and other observable variables. Without falsifiability, there can be no concept of accuracy and hence no valid measure of prediction. Thus for the remainder of this paper, the criteria of falsifiability is attached to all predictions.

A theory is *inconsistent* if it is possible to derive both a statement "A" and its negation "not A" from the theory's assumptions. All other theories are *consistent*. Consistency is a fairly weak criterion to demand of a theory and is guaranteed by a focus on predictive accuracy. Following the standard rules of deductive logic, it is possible to derive *any* statement from the contradictory pair "A" and "not A" (Bergmann, Moor and Nelson 2008: 38, 126-128). Thus an inconsistent theory makes an infinite number of arbitrary predictions, almost all of which will be wrong. To borrow from Morgenthau's terminology, no theory can be consistent with the facts without first being consistent within itself (in Vasquez 1986: 65).

On the surface, *parsimony* is a desirable theoretical property, following as it does from Occam's Razor. And indeed, parsimony has been advanced as a defence of poorly-predictive theories by Waltz (1997) and Huntington (1993), among others. It is unclear why simple theories that fail to make accurate predictions should be regarded charitably. Hippocrates' theory of the four humours is undeniably simpler than modern allopathic medicine, and even possessed (minimal) curative powers (Jóhannsson 2005: 11). At the same time, no sane individual would favour blood-letting over chemotherapy because it is simpler. Many might believe that these aspirations towards simplicity arise from a desire to emulate the physics, where simpler theories have tended to be more accurate.[1] But as Wigner (1960) notes, the "unreasonable effectiveness of mathematics in natural sciences" is

[1] To draw a novel comparison: in the field of Biblical scholarship, parsimony is deliberately avoided in analysis of textual authenticity, as copyists were likely to edit texts in ways which simplified or harmonized difficult passages. Thus the simplest reading was most likely to be the false one (Ehrman 2005: 45-71).

largely fortuitous, and many eminent scientists have warned against an overemphasis on simplicity for aesthetic reasons:

> "If it disagrees with [the empirical evidence], it is wrong. In that simple statement is the key to science. It does not make any difference how beautiful your guess [theory] is. It does not make any difference how smart you are, who made the guess... if it disagrees with [the empirical evidence] it is wrong. That is all there is to it." (Feynman in Brady and Collier 2004: 156)

Of course, simplicity does have some advantages: simple theories are easier to understand and communicate, and arguably to falsify (Popper 1959: 67). Yet these are properties of convenience and scholars are in the business of truth, not convenience. Accuracy should never be sacrificed for simplicity.

Explanatory power is one of the most consistently mentioned attributes of a good theory and often advanced as one of the fundamental purposes of theory-creation (e.g. Babbie 2006: 10; Manheim, Rich and Willnat 2002: 433; Bryman 2008: 6). Yet explanatory power is a poor measure of theory quality for two reasons: explanation is too easy and explanation is *implicit in prediction*. The first issue has long been recognized and as King, Keohane and Verba put it "Any intelligent scholar can come up with a 'plausible' theory for any set of data after the fact, yet to do so demonstrates nothing about the truth of the theory" (1994: 210). This statement does not only apply to social scientists; psychologist Robyn Dawes has shown that under most conditions "Our capability to assimilate known outcomes from the past to favourite causal schema vastly exceeds our ability to predict unknown outcomes in the future" (1993: 1). In other words, explanation is laughably easy, and prediction frustratingly difficult. It is also questionable to what extent explanation can be separated from prediction. Waltz admitted the predictive failures of neorealism, but attempted to justify them by arguing that "a theory's ability to explain is more important than its ability to predict" (Waltz 1997: 916).[1] This claim is nonsensical: if an explanation is falsifiable (and hence expressed in terms of observable variables) then knowledge of the explanation allows prediction as well. If we know *why* something occurs and the causal

[1] In quoting Steven Weinberger to the effect that "There is no theory that is not contradicted by some experiment" (Waltz 1997: 914) Waltz comes dangerously close to rejecting the value of truth entirely.

mechanisms of the explanation can be observed empirically, then it would be strange indeed if we could not extrapolate from the explanation to its consequences. Lastly, it should be noted that there is no non-subjective method to determine whether one explanation is more compelling than another without appealing to predictive accuracy (see Dawes (1993) for a discussion of the problematic psychology behind "compelling" explanations). Thus given the uncertain epistemological status of explanation, it is difficult to accord it more importance than prediction.

The *scope* of a theory, also known as its "generalizability" refers to the universe of case to which the theory applies. A theory has low scope (generalizability) if it applies to very few cases (perhaps only one) and high scope (generalizability) if it applies to a large and varied set of cases. There is no question that high scope theories are easier to test and falsify, as they admit a greater range of observations and higher variability make degenerative ad hoc theorizing more difficult (King, Keohane and Verba 1994). Yet if a theory performs well in a restricted domain, it is bizarre to believe that subsuming it in to a more general but poorly-performing theory is an improvement. Several precise and accurate theories which together span the domain covered by a large and inadequate one are undoubtedly more useful.

Lastly there is the requirement of *cumulativity*: that the researcher build upon pre-existing work and subsume existing empirical content while adding new or novel explanations as well. On the surface this is a reasonable requirement "If we ignore what other people are thinking, or have thought in the past, then rational discussion must come to an end, though each of us may go on happily talking to himself." (Popper 1957: xx). Cumulativity becomes problematic only in application. It is not evident why researchers must build upon potentially degenerative research programmes (Lakatos 1978) and in a low-paradigm (Kuhn 1962) field such as political science, strict cumulativity may be impossible. As Michel Eyquem de Montaigne noted five centuries ago "The novelty of things incites us more than their greatness" (in Brophy et al. 2002: 167). Yet the greatness of Galileo's proof that objects fall at constant speeds was not its novelty to those educated in Aristotelian physics, but rather its truthfulness (predictive accuracy). A focus on the strange and the unintuitive is a subjective criteria that has only a weak link to the pursuit of theoretical knowledge.

1.2 Definitions and concepts

Role of definitions

The need to define one's terms is widely accepted by methodologists (e.g. Manheim, Rich and Willnat 2002: 25-26). It is less clear whether theorists have taken this admonition to heart. Some have finessed problems of definition by avoiding any definition at all. The majority, however, provide a definition early in their writing, but which plays no further role in their argumentation. It is questionable whether these are truly definitions, since they do not constrain the use of terminology or shape the author's argument. The fact that definitions appear once, if at all, in social science papers is worrisome. In mathematics, appeals to definition are ubiquitous, because definitions matter. An entire subdiscipline of biology (taxonomy) exists simply to define and classify organisms. Single-use definitions may provide clarity to readers, but the main function of definitions is a logical one, as consistent use of definitions will inevitably shape the contours of an argument and hence its conclusions.

Characteristics of a good definition

While much ink has been spilled on the characteristics of a good theory, far less effort has been devoted to the characteristics of good definitions for theoretical concepts. Work by Manheim, Rich and Willnat (2002: 21-23) is a welcome exception and the approach developed here builds on their treatment of operationalization. A good definition of a theoretical concept must fulfill three criteria: exhaustive, exclusive and analytic. These criteria apply to definitions which are at least partially inductive, in that the researcher has pre-existing notions about the empirical content of the concept (i.e. what it does and does not include). The challenge is thus to find rules (syntax) which accurately encapsulate these intuitive ideas (semantics). The criteria below pass no judgement on the correctness of these intuitions, but merely on the definition's ability to capture it. The definitions in chapter 3 will be evaluated according to these criteria, and as an example, various definitions of the state are evaluated below.

> Exhaustive: The definition must include all entities which satisfy the semantic criteria. A definition of modern states as "all member-countries of the United Nations" would fail this test because Communist China was excluded from 1945 to 1971.
> Exclusive: The definition must not admit any entity which does not satisfy the semantic criteria. Thus a definition of statehood which applied to regional warlords or which could inadvertently classify alliance blocs as single states would be inadmissible.
> Analytic: The definition must yield a response of yes/no, in/out for any entity. Max Weber's definition of modern states as the organization whose "staff successfully upholds a claim on the monopoly of the legitimate use of violence" (Weber 1919) is not analytic *as specified* since the concept of legitimacy can be interpreted in many possible ways. This definition could be made analytic by dropping the legitimacy requirement, or by rigorously defining legitimacy (e.g. Schutz and Slater (Eds) 1990).

These criteria are fairly simple and do not cover the whole range of issues associated with theory crafting. Theoretical import and conceptual stretching, among others, are not addressed, but these issues are complex enough to deserve a more nuanced treatment than can be provided here. The guidelines above specify merely whether a definition can fulfill is core function: to provide conceptual organization of empirical phenomena.

1.3 Time

Few social scientists deal explicitly with the theoretical implications of time. And yet issues related to time are among the most fundamental decisions one can make in one's analytical framework, and they will have deep impacts on one's conclusions. This section introduces different notions of time, surveys approaches to time used in economics and political science, and lastly proposes an approach to time which is well-suited to the purposes of international relations theorizing.

Statics vs. dynamics

An important distinction in the theoretical treatment of time is between static and dynamic models. Static models deal only with equilibrium or stationary states (Samuelson 1941: 98-102), while dynamic models "determine the behaviour through [continuous] time of all variables from arbitrary initial conditions" (Samuelson 1941: 100). Static analysis is simpler but less powerful than dynamic analysis, and is typically the first theoretical approach to a topic.

Static models give rise to predictions about equilibrium states and in particular how these states will change following a shock to the system. The study of these predictions is known as comparative statics and is carried out in section 3.4.

Time in economics

Time has been a central concern of microeconomists since David Ricardo used the value of money over time to demolish the labour theory of value in under four pages (1909: 35-39). Thus the great economic systematizer Alfred Marshall declared that:

> "The element of time is a chief cause of these difficulties in economics which make it necessary for man with his limited powers to go step by step; breaking up a complex question, studying but one bit at a time, and at last combining his partial solutions into a more or less complete solution to the whole riddle." (1961: 366)

In order to proceed with the economic analysis of time, Marshall introduced the concept of qualitative time, which consisted of three periods: the short run, long run and very long run. What defined each period was not objective or calendar time, but whether a given factor of production was variable or fixed (Marshall 1961: 369-371). Over the short run, a firm can vary its labour input, but the capital stock and technology were held fixed. The long run was characterized by variable labour and capital, but fixed technology. Over the very long run, labour, capital and technology could all vary.

Time is also an important issue in game theory and modelling. Here again, time is not defined by clock or calendar time, but rather by a player's state of knowledge: "a move later in time, but in ignorance of the opponent's choice, is considered simultaneous with the latter" (Hirschleifer in Hartley and Sandler 1995: 168). As in microeconomics, time is divided qualitatively, and the criterion for these divisions is the status of a theoretically-important variable.

Time in political science

The role of time in security studies dates back to Hobbes, who made it explicit that:

> "...the notion of *Time* [italics in the original] is to be considered in the nature of Warre: as it is in the nature of Weather. For as the nature of Foule weather, lyeth not in a shower or two of rain, but in an inclination to do so for many days together; So the nature of War, consisteth not of actual fighting; but in the known disposition thereto, during all time there is no assurance to the contrary. All other time is PEACE." (1988: 64)

Alfred T. Mahan was equally strident, stating that time was "everywhere admitted a supreme factor in war" (1892: 48). Yet modern treatments of war initiation rarely address time (with the obvious exception of crisis studies). An exception to this is Brawley (2004) who examined how decisions about arming, appeasing and war could differ over short and long time horizons. Even in studies of war termination or war duration, which use time as the dependent variable, interest in time is purely econometric (e.g. King and Zheng 2001) rather than theoretical. For the most part, few security theorists take time seriously.

Arms race studies are a different matter entirely. Under the influence of Richardson (1960) most arms race models are in continuous time. As Brito and Intriligator argue this "was unfortunate... because continuous time makes it very difficult to model other essential features of arms races, such as learning, strategic behaviour, uncertainty, budget cycles and lags"(in Hartley and Sandler 1995).

Political qualitative time

This section introduces a qualitative political time scale which will be used for the remainder of this paper. Political qualitative time is a deliberate "analytical fiction" which exists to simplify theorizing about conflict. It does so by specifying the factors in play over different time horizons, and by drawing our attention to the differences between each time period. The descriptions below refer informally to concepts that are rigorously defined in section 3.1.

> Short Run: The political short run is the time horizon over which war can be declared and decided using existing military assets. By assumption, since wars are decided in this period, only pre-existing force levels determine the outcome of the conflict. National resources and the allocation of those resources are held fixed.
>
> Long Run: Over the political long run, a state's resource endowment and technology are held fixed, but the allocation of that endowment between military and civilian uses my vary.
>
> Very Long Run: All factors may vary over the very long run, including resource allocation, the national resource endowment and technology.

These time scales are nested within one another, in the sense that any change which could occur in the short run can also occur in to long run as well. Thus an arms race occurring over the political long run can be interrupted by a war.

II. Literature Review

2.1 Stylized Facts

This section strategically reviews and summarizes the academic literature on arms racing, war initiation and war outcomes (victory). This goal of this review is to locate "stylized facts." Kaldor (1957) is credited with introducing the notion of stylized facts, which are empirical generalizations which, although not true in all cases or at all times, are consistent enough to be used for theoretical and heuristic purposes. They both to inspire new theories, and also specify constraints on model- and theory-building. Models which fail to predict a field's stylized facts are generally unacceptable, since they contradict the most solid empirical evidence available at the time.

This section is not a comprehensive review of the relevant literature. This is partly a function of space constraints, but also the weak state of knowledge transmission in political science. A sense of this weakness can be gained by comparing political science to medicine and health policy, two empirically "messy" fields which produce massive amounts of research data and which still manage to reach consensus on basic facts. Knowledge transmission in health relies on systematic reviews (transparent, replicable reviews informed by library information science) and meta-analysis (statistical techniques that pool the results of multiple quantitative studies). These knowledge aggregation techniques are supported by "hierarchies of evidence" (e.g. Evans 2003) that grade study methodology by shared criteria. In contrast, political science relies on "narrative" reviews whose results depend purely on the author's field knowledge. In some cases the quality can be quite high (e.g. Levy in Tetlock 1989), but it is still unclear how the reviewer has reached a given conclusion or what criteria determined which literature was included.[1]

This paper will not resolve those difficulties. Instead, it continues the narrative tradition, with a particular focus on empirical papers (both statistical papers and well-researched case studies) and on theoretical work in the rational choice tradition. It begins with arms racing, then proceeds to war initiation and war termination (military victory).

Arms Racing

Theoretical definitions of arms races are few in number and relatively consistent with one another. Gray (1971: 41) defines an arms race as:

> "(1) Two or more parties, conscious of their antagonism.
> (2) They must structure their armed forces with attention to the probable effectiveness of the forces in combat with, or as a deterrent to, the other arms race participants.
> (3) They must compete in terms of quantity (men, weapons) and/or quality (men, weapons, doctrine, deployment).
> (4) There must be rapid increases in quantity and/or improvements in quality."

Gray's notion of purposefulness is echoed by Burns who requires that "an increase or improvement [in arms] must be made on account of a… belief about the state of some other power's arrangements." (1959: 324) Burns also raises the issue of complimentarity, asking if an arms race can exist between navies on the one hand, and coastal fortresses on the other. Huntington (1958) answers this question in the affirmative, pointing out that arms races among air forces typically pit fighters against bombers as well as against each other. Huntington's well-

[1] Political science reviews rarely include so-called "grey literature": government reports, papers produced by thinktanks, conference papers, manuscripts in progress, etc.

known (1958) definition restricts arms races to two nations arming competitively against each other and bears many similarities to that provided by Gray.

Empirical definitions are another matter entirely. Most consist of a minimalist definition (e.g. "dynamic process of interaction between countries in their acquisition of weapons" (Brito and Intriligator in Hartley and Sandler 1995: 115)) paired with a minimum change in armaments levels (e.g. 8% per year in expenditures for three years (Gibler et al. 2005)). Often, the list of potential arms races is restricted to Militarized Interstate Disputes. The rate of change requirement is subject to intense debate in the empirical literature. Wallace (1979) required that the percentage increase in military expenditures of the two participants in an arms race exceed 10% when multiplied together. Diehl (1983) uses an average growth rate of 8% or higher by both sides over the three years preceding a crisis, a decision which would later motivate Wallace (1982) to reanalyze his original data using a three-year time horizon as well. Horn (1987) compares the rate of arms build-ups before a crisis to the average increase in military spending over the entire Correlates of War sample period (1816 to 1980 at the time) and required the tempo of the arms race to be accelerating over time. Others, (Ward 1984; Bolks and Stoll 2000) have used the actual weapon stocks of arms race participants, rather than military expenditures, as a measure of arms racing, although the arms races chosen for study were defined by *a priori* historical consensus.

These definitional issues are critically important because they determine the answer to debates over the link between arms racing and war, an issue to which we now turn. Richardson (1960) proposed that arms races which were accelerating over time would inevitably lead to war, and provided evidence from the World Wars to support his conclusion. Wallace (1979, 1982) found a significant relationship between arms racing and war, with 23 of 28 arms races ending in war, versus only 3 of 68 cases which did not involve a mutual military buildup. Diehl's (1983) use of a smaller dispute set and a more lenient definition of arms race lead him to conclude that the arms racing-war relationship was spurious. Sample (1997) resolved much of the controversy by comparing various definitions of arms races with dispute lists. She found that for all combinations of definitions and dispute lists, virtually all arms races escalate to war, either during the arms race itself or within five years of the arms race ending. Additionally, Sample confirms Diehl's (1983) result that unilateral build-ups are less likely to result in war than competitive armaments processes.

Multivariate analyses of arms races are rare, consisting of Wallace (1980), Sample (1998) and a few specialized studies of single arms races(e.g. Ward 1984). Wallace (1980) examines the effects of a victory in the arms race (victory being defined as 50% superiority or greater military expenditures) going to either the revisionist or status quo power. He concludes that arms races won by revisionist states are 2.5 times more likely to end in war than those won by revisionist powers. Sample (1997) finds that after eliminating controversial dyads, arms races are strongly related to the outbreak of war, as are territorial disputes, while nuclear weapons greatly reduce the risk of escalation. She finds that power transitions, rapid approaches to parity and the size of the defence burden are *not* significant predictors of war initiation. A weakness of Sample's otherwise excellent study is that it relies on dyads, but includes a great number of actor-level variables. Thus her measure of high defence burden is coded as present in a given dyad-year if *either* state possesses abnormally high expenditures. Yet the burden of defence spending is actor-specific, and will be felt by that actor only. Thus the interpretation of her conclusions is ambiguous for several variables.

Another important issue in arms race modelling is how to integrate economic considerations. As Anderton put it "Fundamentally, an arms race involves political-economic choice. The nations (groups, leaders) involved in an arms race must decide how to allocate scarce resources to defence and non-defence programs subject to political constraints" (1989: 355). Yet this tradeoff is often modelled simplistically - if at all - by most authors. Richardson (1960) included current military spending as a “drag” term in his model, but this is only a rough estimate of the opportunity cost of military spending. A related problem is the use of a very crude measure of defence-related utility. Papers by Brito and Intriligator (in Hartley and Sandler, 1995) and Dunne (in Hartley and Sandler, 1995) include a “security” variable in their utility function, even though neither model allows for war. Yet arguably, that the concept of security is meaningless in the absence of war or other threats to state survival. Thus the literature appears to have ignored Anderton’s advice to “capture the political-economic choice problem faced by policymakers” (1989: 357). And as a result, Powell was forced to conclude from his literature review of arms racing that political scientists “lack a fully developed theory of when a state should race” (2000: 251).

Lastly, scholars often debate the degree of farsightedness or myopia with which arms races are conducted (Gray 1971, Burns 1959). The well known “spiral” model (Jervis 1976) posits a simple action-reaction dynamic in which states suffer from the “fallacy of the last move” and never consider the influence of current moves on the future actions of their adversary. Some believe that this myopia exists and arises from human cognitive deficiencies (Klein 1998) but as Glaser points out experts such as statisticians and analysts are trained to overcome such biases and thus “national level misperceptions… seem more likely to reflect the failure of national-level evaluative capabilities than individual cognitive limitations” (1992: 514-515). Modellers have diverged on this issue: Richardson describes his equations as reflecting “unthinking” policy responses, (1960:12) while modern game theory models rely fundamentally on rational expectations and reaction curves (e.g. Powell 1993)

War Initiation

The vast literature on war initiation is impossible to summarize, both because of its size, and also the lack of consensus on most issues. This section highlights a few broad empirical findings and non-findings, but focuses mainly on theoretical explanations of war, grouped in to the following categories: mistake theories, expected utility theory, signalling and information theories, contracting problems and compound gains theories.

Mistake theories hold that was is fundamentally irrational and search for mechanisms which might lead to war breaking out in spite of this. Two of the most popular mechanisms are cognitive biases/misperceptions and state capture by substate actors with private interests. An example of the first category is Jervis (1976) presentation of the spiral model, which as he pointed out, is correct only if statesmen do not understand or follow its prescriptions. Other important contributors include Levy (1997) on prospect theory and Janis (1982) on groupthink. Examples of state capture range from Schumpeter's atavistic elites (1951) to standard Marxist accounts of international conflict (e.g. Chandra, Gosh and Kumar (Eds) 2004). Mistake theories have not been persuasive in the study of international relations. As Jervis' comment above highlights, such theories imply that political leaders have for centuries repeated mistakes that are readily apparent to political scientists, and furthermore, that they will continue to commit such errors indefinitely. Mistake theories are also silent on the timing of war initiation – if misperceptions and biases are constants of human or organizational cognition, this cannot explain the intermittent nature of war.

Expected utility theories (henceforth EUT) are in a sense the "naive" rationalist approach to war initiation. Simple to understand (although not necessarily easy to operationalize) they predict that if the probability-discounted benefits of war outweigh the probability-discounted costs, then states should initiate conflict. The strongest support for this view is the disproportionate number of wars which are won by the aggressor: 70% for all wars since 1815 and 55% for wars post-1945 (Lindley and Schildkraut 2005: 1). EUT often acts as an implicit theory underlying realist arguments about war (which see war as a rational policy tool), but has fallen out of favour as an explicit approach to conflict. The primary reason for this is a compelling set of critiques advanced by Fearon (1995), to which we now turn.

Fearon noted that if we take state rationality seriously, then the destructive nature of war presents a dilemma, which he calls "the inefficiency puzzle of war" (1995: 381) or as Mahan put it, the fact that "nations are under no illusions as to the unprofitableness of war itself" (1912:126). War consumes resources before reaching an outcome, and is thus inefficient relative to a negotiated settlement, which would leave both parties better off even if it replicated the results arrived at on the battlefield. Why, then, do rational states go to war?

Fearon's most popular answer is private information. Private information exists whenever states know more about their own forces than those of their enemies, potentially leading them to initiate unwinnable wars. Private information in this context can include force levels, weapon quality, war plans, resolve, public morale, etc. If this private information were common knowledge, then states could agree on the likely winner, or at least on the distribution of probable outcomes. From this mutual agreement arises the possibility of a negotiated settlement which avoids the destruction of war. Yet states have strong incentives to misrepresent their private information in order to gain the upper hand at the bargaining table. Exaggerated military prowess would translate directly in to improved negotiated settlements under a rationalist model, rendering fatally suspect all self-reported data and signalling. And indeed, as Clausewitz noted, variables such as national will can only ever be imperfectly approximated, despite its overwhelming importance to war outcomes (1982: 109-110). The combination of unobservable private information and incentives to misrepresent requires that war be used as a signalling mechanism or costly bargaining process (Brito and Intriligator 1985; Sanchez-Pages 2004, Reiter 2005).[1]

[1] There is also the problem which, for lack of a better term, can be called contingent information. Contingent information is analogous to Heisenberg Uncertainty Principle, in that revealing the contingent information changes the outcome which that information was intended to influence. Thus the "perfect information" case is radically different from the real world, and cannot form a basis for negotiations. The most obvious example concerns war plans: Germany's Schleiffen Plan interacted with the French Plan XVII to the detriment of France – yet it is impossible to reveal this advantage in order to profit at the bargaining table, as it would merely motivate France to choose a

Fearon's second argument, which is also taken up in Powell (2006), is the contracting problem. The underlying anarchy of the international system means that contracts cannot be enforced by third parties, and must be "self-enforcing" through the self-interest of the states involved. Yet if a state is strong enough to extract negotiated concessions from a weaker opponent, it has no incentive to honour the contract, and every incentive to demand even more after receiving its initial payoff. Knowing this, the weaker party will refuse to yield and conflict becomes inevitable. Appeals to anarchy as a permissive cause of war are common since Morgenthau (1948) and find their fullest expression in Waltz (1979). While they do resolve the inefficiency puzzle of war, they have relatively little predictive power, since anarchy is constant in the system, but war is not.

Finally, some approaches question the inefficiency puzzle, rather than attempting to solve it. These authors acknowledge that war is indeed an inefficient process initially (more accurately, over the political short run), but point out that compound gains from victorious wars can outweigh the one-time costs of fighting (see for example Garfinkle and Skaperdas 2000; Skaperdas and Syropoulos 1996 and especially Powell 1993). Additionally, the ability to convert war industries to civilian use after completely eradicating an opponent provides a further incentive to go to war, in the form of a "peace dividend" over and above resources seized from the opponent.

In addition to the theoretical debates over the rationality of war, scholars have raised questions about the theoretical importance of preventive and pre-emptive wars.[1] Preventive wars figure importantly in Power Transition Theory (Organski and Kugler 1981) and pre-emptive wars are predicted by rationalist models of arms racing (e.g. Brito and Intriligator in Hartley and Sandler 1995). Reiter (1995)

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new strategy. Likewise, codebreaking, highly-placed spy rings and secret alliances all influence war outcomes, but cannot inform pre-war diplomacy.

[1] For the purposes of this paper, preventive wars are defined as all wars launched to prevent a long-run shift in the balance of power. Pre-emptive wars are those launched due to short-run considerations, generally in the hopes of seizing the initiative or achieving surprise.

points out, however, that only 3 of the past 67 Correlates of War project wars are classified as pre-emptive conflicts – a mere 4.5%. Reiter speculates that this occurs because the political costs associated with unprovoked aggression outweigh any military benefits (1995: 33). This was certainly the case for the Anglo-German naval rivalry: although Tirpitz believed the German navy was passing through a "danger zone" in which Britain would be tempted to launch a pre-emptive strike, British political leaders repeatedly denied requests by the Admiralty to "Copenhagen" the German High Seas Fleet (Gray 1971: 72). Similar findings apply to preventive wars as well, and both Howard (1983:12) and Blainey (1988: 127-145) find that preventive wars are rare events in the modern state system. Even more worrisome from a rationalist perspective is the tendency for rising nations to pre-empt themselves and begin wars while still inferior to their adversaries (Organski and Kugler, 1981).

A final group of theories of war initiation are those which focus on the offensive-defensive balance, which are reviewed at length due to their potential to contribute to this paper's model. Offence-defence theory (ODT) holds that the relative ease of attack or defence in the international system determines the initiation and outcomes of international conflict. As offence becomes more effective, war break out more frequently, arms races become more intense, and states aggregate in to empires (Van Evera in Brown et al. 2004). Yet as Biddle puts it "Offence-defence theory is intuitively appealing… but this intuition has never been fully developed" (2001: 742). This is most clear with respect to definitions of the offence-defence balance, which range widely in the factors they consider. The most common form of definition is based on the acquisition of territory (which excludes *a priori* naval, air, nuclear and guerrilla warfare) and some measure of the effort involved. Glaser's definition is typical: "[Relative] investments in forces that support offensive missions compared to investments in forces supporting defensive missions" (1994: 61). Similar definitions are given by Jervis (1978: 170) using territory rather than missions and Schelling (1984: 274) who focuses on relative loss of life. Many definitions go beyond purely military factors, so that Van Evera (in Brown et al. 2004) also includes diplomacy, while some include the attacker's ability to exploit conquered territory (Hopf 1991).

There are a number of problems with even the minimalist definition presented above. A levels of analysis problem exists at the heart of ODT, since strategic defence may often require local, tactical counterattacks, making it difficult to easily classify attackers and defenders in all cases. The offence-defence balance will also depend in part on the objective chosen – more modest goals are more easily attained (Biddle 2001: 766, 771; Biddle 2004: 311), and this may endogenize the offence-defence balance. The economic definition provided by Glaser is "unmeasureable even in principle" (Levy 1984: 225), while the Van Evera's inclusion of diplomacy conflates ODT with balance of power politics and is a clearcut example of conceptual stretching.

Another source of confusion arises when scholars conflate the offence-defence balance with determinate outcomes, rather than probability or likelihood of victory. This leads Jervis (1978: 187) to make the ridiculous claim that the balance can shift over the course of a single battle or campaign. Similarly, when Glaser and Kaufmann (2004: 269) claim that raw power or military skill may "overwhelm" or alter the offence-defence balance, they commit a similar error by assuming that ODT predicts continuous offensive or defensive victories. Levy sums up the correct reading of the theory when he says "To say that the balance of military technology… favours the offence does *not* mean that the attacker is likely to win [in all scenarios]. The minimum ratio of forces needed by the attacker is analytically distinct from the actual balance of forces possessed by two adversaries in a particular situation" (1984: 66).

The role of perceptions and rationality is another important, but controversial issue. Van Evera (1984) was one of the first to note that policymakers might fail to correctly assess the offence-defence balance, as illustrated by the war plans of all nations during World War 1. Shimshoni (1993/1994) has argued both that perceptions may diverge from reality, but also that the offence-defence balance can be influenced by what he calls "military entrepreneurialism" on the part of actors. This paper will deal only with the full information, exogenous balance case, and so neither debate is not directly relevant to the model.

Military Victory

Although "power" remains a vague and sometimes tautological concept in International Relations scholarship (Lamborn 1991: 14), the analysis of military victory has benefited from a tight focus on the link between military power and war termination. Yet as Biddle notes, many traditional measures of military power, such as GDP, perform poorly as predictors of war outcomes (2004: 2). This section briefly reviews the literature on military victory, omitting the role of ODT, which was discussed above.

According to Clausewitz, numbers – of troops, fighting platforms, munitions, etc. – form the foundation of military outcomes:

> "If we strip away the combat of all modifications which it may undergo according to its immediate purpose and the circumstances from which it proceeds, lastly if we set aside the valour of the troops... then there remains only the bare conception of the combat, that is a combat without form, in which we can distinguish nothing by the number of combatants... Thus numbers will therefore determine victory." (1982: 265)

Yet at the same time, he noted that the number of abstractions required to reach this conclusion, which shows that military power is determined by more than merely the size of armies, even if "numbers must, at last, overpower everything else" (1982: 265). Analytically, this insight is m modelled using what Hirshleifer (2000) termed a "contest success function" (CSF), which maps force levels of opposing states on to war outcomes. The most common type of CSF is the ratio form, in which relative differences in force levels determine war outcomes. Ratio form CSFs have two important implications: zero investment by one side guarantees total defeat (unless neither side invests in armaments) and secondly that, assuming that the ratio of forces remains constant, the scale of a conflict is irrelevant to its outcome (2:1 odds generate similar outcomes regardless of whether the size of the conflict is thousands or millions of combatants). The output of a CSF is typically expressed as a number in the interval 0 to 1; by assuming risk neutrality, this number can be interpreted as either a state's probability of total victory, or the share of the objective it obtains (Garfinkle and Skaperdas in Hartley and Sandler 1995).

CSF functions are highly abstract and theoretical concepts developed by academics. Thu is is important to also examine how military experts approach the same problem. Most political scientists are familiar with the 3:1 rule, which suggests that in order to achieve an offensive breakthrough, the attacker must outnumber the defender by a factor of 3 or more. This rule has received widespread coverage, and despite a few detractors (see Mearsheimer 1989 for a discussion) it has met with general approval (e.g. Hart 1930: 434-435, Dunnigan 2003: 5; Gray 1971: 43, 109; Dupuy 1979: 60). More complex military models exist, such as Lancaster equations or sophisticated military-strategic models which allow for concentration and reserves (Huber in Avenhaus et al. 1991). Interestingly, many of these models can be reduced to single-output functions which are thus consistent with the model that is developed below.

III. Two-Nation Arms Race Model

The model which will be developed in this chapter has five primitive notions: resources, value, force, governments and war. From these primitive notions, four model components will be defined. Lastly, the model makes four key assumptions about the nature of inter-state conflict, each of which will be presented and defended. In the final section of this chapter, the model's results will be presented.

3.1 Primitive Notions

A primitive notion is a basic concept in a model which is not defined in terms of any other within-model concepts. Primitive notions thus form the logical foundation upon which a theory rests, as they are defined either informally or using concepts outside the scope of theory itself. In Peano-Dedekind arithmetic, for example, the number zero and the successor function are primitive notions from which all numbers and all basic mathematical operations are constructed. In constructivist theories of international relations, identity is a primitive notion, as it is not defined in terms of more basic theoretical concepts. In economics, production functions are primitive notions, while supply curves are not, since supply curves are merely the aggregation of many firms' production functions.

Resources

A state's resources (the term resource base and resource endowment will be used interchangeably) is a variable which subsumes raw materials, physical, human and social capital, labour force, technology, organization and all other productive inputs of a state's economy. The importance of economics to statecraft has long been recognized, beginning with Cicero's famous declaration that "Money is the sinews of war" and continuing to modern attempts to rank the power of nations on the basis of their resource endowments (Morgenthau 1978: 122, 127-155; German 1960 *passim*; Ray 1980 *passim*).

Formally a state's resource endowment is a flow which is assumed to be fixed at some level S except in the very long run. Very long run growth of a state's resource endowment is assumed to be constant and exogenous, an assumption made mainly for simplicity, but which is in line with orthodox economic growth theory (Manikw, Romer and Weil 1992). Resources are assumed to be finite and therefore scarce relative to states' consumption and security needs. Lastly, following Niou, Ordeshook and Rose (1989:76), it is assumed that any state whose resource endowment is reduced to 0 is eliminated from the international system.

One could challenge the exogeneity assumption by pointing out that military (force) spending is typically seen as a drag on the economy (Kennedy 1987). Econometric evidence on this point is mixed; some find that small levels of military expenditures can boost GDP growth (Håkan and Wiberg in Gledditsch and Njølstad 1990), while most find zero or slight negative impacts on growth

(Fischer and Brauer 2003:228; Lai 201: 150,153; Dunne in Hartley and Sandler 1995: 423-424). For now, growth rates are assumed to be exogenous for the sake of simplicity, but it is recognized that they may need to be endogenized by more complicated models.

Lastly, it is assumed that increases in military production are limited to a fixed rate which is proportional to the state's resource base. The exact size of this production limit is subject to considerable uncertainty, as historically, governments varied in their ability to extract resources from domestic constituencies. Periclean Athens, for example, spent about 7% of GNP on warfighting, while the military expenditures of Florence under the Medici ranged from 3% of GDP in times of peace to 20% during war time (Ferguson 2001: 44-45). Even modern nation states proved unequal in their mobilization potential and during World War 2, the percentage of GDP spent on the military ranged from a low of 40% in the United States, to 50% in Germany, 55% in Britain and probably higher in the Soviet Union (Knorr 1970:41). This issue is further explored the in section 3.3.

Lastly there is the question of resource fungibility. One could argue, after Brawley (2004) that "policymakers must take in to account that wealth does not perfectly translate in to power" (2004:7). The issue of resource fungibility between force and value is an important one, but it is dealt with invisibly in the model, through the precise form of a state's force and value functions.

Value

The concept of value used in this paper is analogous to that of utility in economics: value is something that is desired in all situations (unlike force, which is valuable only in the presence of a hostile adversary). The need for separate terminology arises because value is a physical commodity, representing discretionary consumption on the part of the state's government. Value is a flow generated from a state's resource base by a *value function*, which is assumed to be continuous, differentiable, upward sloping and subject to diminishing marginal returns. States are assumed to maximize discounted present value at all times. States discount future value consumption using a fixed exponential discount rate δ, with $0<\delta<1$.

Why do states maximize value? In some political systems, value may accrue directly to government officials through corruption, inflated salaries or in aristocratic regimes, via rents paid to feudal officeholders (Huntington 1968; Bueno de Mesquita, Smith, Siverson and Morrow 2003; Kautsky 1982). But more generally, value can be spent on popularly-desired public goods (the consumption of which benefits the government regardless of whether it is seeking reelection or merely pacifying the masses) or on projects of idiosyncratic interest to current officeholders (Johnson's "Great Society" initiative, Khrushchev's "Virgin Lands" campaign and Pierre Trudeau's National Energy Program are all examples of such policy goals). What unifies each of these examples is that value represents a desirable goal which is (at least in theory) impossible to saturate.

The inclusion of value as an ultimate objective is a small but fundamental improvement over most existing realist theories. It is true that realist models of conflict behaviour rarely include economic factors (Brawley 2004: 77), but the problem is even more basic: without an objective to strive towards (even if a state's appetite for value can never be fully satiated) realist states have no motivation to engage in their relentless struggle for power, since as Narizny observed "Security is not an object unto itself; it has no meaning in isolation of interests"(2003: 185). Consider the following thought experiment: a rising great power, through guile, strategy, and fortune, defeats all of its major rivals and establishes a global hegemony. What happens next? Conventional realist theories whether they focus on the pursuit of security or power , have no guidance to offer and in fact are effectively undefined for this scenario. As "Hirshleifer put it: "An awkward modelling problem arises … once war has occurred, what next? In such models the advent of war means ‘the end of history’” (in Hartley and Sandler 1995). Morgenthau was quite convincing to early eralists when he argued that:

> “Whatever the ultimate aims of international politics, power is always the immediate aim. Statesmen and peoples may ultimately seek freedom, security, prosperity or power itself... but whenever they seek to realize their goal by means of international politics, they do so by striving for power.” (in Vasquez 1986: 329)

But they have since lost sight of the need for an ultimate goal, one which gives purpose and direction to the unending contest of realpolitik.

Force

The concept of “force” represents military assets which allow a state to seize resources from adversaries or prevent such attempts against its own resource base. “Force” is used in this context as a more precise term than “power”, since it applies only to physical, social and human capital which can be used in conventional warfare.[1] If capability as Holsti put it “is always capability to *do* something” (1988:143) then force is the ability to transfer resources to the victor from the vanquish, against the will of the latter.

A nation generates force from its resource base using a *force function* that is assumed to be continuous, differentiable, upward sloping and subject to diminishing marginal returns. Force, like value, is a flow, but unlike value, which is consumed in the same period that it is produced, force accumulates as a stock. For the rest of this paper, all references to “force” or “force stock” or “force inventory” will refer to the total stock of force at a state’s disposal. Any references to force as a single-period flow will use the term “incremental force” or “marginal force”.

A state’s force stock is assumed to depreciate at rate d , which will be arbitrarily set at 10% per period, a figure in line with econometric growth literature on economy-wide depreciation rates and the few available estimates of military

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[1] The elements of the force function are left intentionally broad to accommodate the many non-material factors which influence military power, such as “the military revolution of the Bronze Age was more in the development of truly complex societies than in weapons technology” (Spoulding and Hoffman 1994: 1).

capital depreciation (Romer in Baro 1989: 60; Baffes and Shaw 1993: 5).[1] Because changes in force levels take place over the political long run, force stocks are assumed to always be at their equilibrium values. Thus for a given rate of investment in incremental force a state's equilibrium force level will be:

$f_t = f_m + f_{t-1} - d \cdot f_{t-1}$

by definition, in equilibrium, $f_t = f_{t-1}$ thus we have:

$f_t = f_m + f_t - d \cdot f_t$

$f_t = f_m + (1-d) \cdot f_t$

substituting d = 0.10, we have

$f_t = f_m + 0.9 \cdot f_t$

$0.1 \cdot f_t = f_m$

$f_t = 10 \cdot f_m$

(where f_m represents marginal investment in force, f_t is the force stock in period t, f_{t-1} is the force stock in the previous period and *d* is the depreciation rate)

Force is also assumed to be undifferentiated variable which can me measured unidimensionally. Such an approach could be criticized on a number of grounds. Cohen, for example, argues that "[Medieval] militaries defied comparison; their strength varied greatly depending on who and where they were fighting" (1996: 53), a point which is reinforced strongly by Machiavelli's writings in the *Art of War* (2001: 46-50). More broadly, this raises the issue of optimal force mixing (what proportion of archers to men-at-arms, or rifle division to armoured divisions or ICBMS to SLBMs?) and also the difficulty of aggregating across national militaries (Radner in Levy 1984: 226). Lastly, there are theoretical reasons to separate different types of force, with conventional versus strategic weapons being the most obvious division.

The first point has already been addressed by military modelling experts on a purely theoretical basis through the use of Hembold functions (Anderton 1992). Hembold functions are a generalization of Lancaster functions which capture the

[1] A lower bound for *d* would be either 3% or 4% (identical to the economy-wide depreciation rate), but the actual depreciation rate of the force stock is likely to be higher for two reasons. Firstly, because military capital is probably depreciates faster than civilian capital (due to more intensive use) and secondly, because the force stock as defined here also includes consumables (ammunition, food, fuel, etc). Thus the figure of 10% given by Baffes and Shaw was preferred, as it uses the "perpetual inventory" method which can account for both of these factors.

battlefield interactions between different types of military units.[1] Thus by expressing force as the outcome of a Hembold function, all force-mixing decisions can be solved via a game theory approach, since nations would compare all possible force mixes and select Nash equilibrium force posture. Given identical technology and resources, this solution would be symmetric in all important respects. As a result, the entire operation of selecting a force mixture would constitute an essentially "invisible" step in the model without changing any of its conclusions.

The issue of comparing force across nations is more complicated. The first point that must be made is that scholarly attempts to do so are ubiquitous, at varying degrees of sophistication; examples include "armoured division equivalents" (Dupuy 1979: 63-64) to a "lethality index" of all weapons from the crossbow to the machinegun (Albrecht, Gledditsch and Njølstad 1990: 98). Ultimately though, as the following quotation makes clear, political leaders are habituated to making "fuzzy" comparisons of force levels:

> "The scales of the balance of power will never be exactly poise, nor is the precise point of equality either discernable or necessary to be discerned. It is sufficient in this, as in other human affairs, that the deviation not be too great." (Lord Bolinbroke, 18th century British Foreign Minister, quoted in Maurseth 1964:125)

Thus although India and Pakistan purchased military hardware at very different levels of quality from their superpower patrons, the timing of these reciprocal purchases suggests that they were still intended to offset each other (Banjeri 1991: 73). This in turn implies that both states perceived shifts in the balance of power and were attempting to match those shifts to the best of their abilities.

Finally this paper assumes that there are no theoretically important distinctions among different types of military hardware or personnel. In the case of nuclear and conventional weapons that is clearly indefensible. In order to accurately model simultaneous nuclear-conventional arms races, two arms race models would be required, along with a bridging theory of some sort. The development of

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[1] To use a medieval example, if pikemen are effective against knights, knights effective against archers and archers against pikemen, a Hembold function can correctly adjust battlefield outcomes to reflect the effects of different proportions of troop types in each sides forces.

such a bridging theory is beyond the scope of this paper. But some authors (Zinne and Gilespie 1976: 260) have argued that *all* periods of history are characterized by the coexistence of conventional weapons (for use in limited warfare) and strategic weapons (weapons whose goal is the elimination of a major power from the international system). In particular, they give the example of the battleship in the pre-World War 2 period of the 20th century (Zinne and Gilespie 1976: 277). This typology ignores a number of basic historical facts and thus lacks empirical validation. Even if one uses the example of battleships in the early 20th century (ignoring for a moment their rapid displacement by aircraft carriers in the 1920s and 30s) the two major powers that were eliminated from the system following World War 1 (Austria-Hungary and the Tsarist Russia) were both land powers who fought no major naval engagements during the entire conflict. And while Anglo-German naval rivalry may have provoked the conflict, the two surface fleets fought only one inconclusive engagement. Finally, on the issue of requiring a “strategic” weapon to eliminate a rival power, there is Schelling’s macabre observation that: “there is not much that nuclear weapons can do that cannot be done with an ice pick” (1962: 18). Thus the unidimensionality of force seems to be a reasonable definition of the concept.

Finally, one can point out that statesmen are accustomed to making such calculations on a daily basis. Thus the Japanese general staff estimated that the “real value” of their 24 Manchurian division was actually 7 or 8 division (Morgan in Knorr and Morgan 1984: 71), while Wehrmacht commanders estimated that one German division was equivalent to 3 Russian ones (Kam 2004: 105).

War

Formally, war is defined in this model as a contest between states over resources. While states could presumably choose a number among a range of war objectives, for simplicity’s sake, the model will restrict itself to total war in which the loser’s entire resource base is at stake. In determining the payoff of war, it is recognized that war destroys some of the resources in question (Fearon 1995), but also that

“Wars are fought because decision makers conclude that they will be better off after the war than they would be if they did not engage in them” (Possony and Purnelle: 178). Thus a fraction p of the target’s resource base is transferred to the victor, while a fraction 1-p is destroyed. Here, p can represent both conquest and administration (as in Morocco’s occupation of Western Sahara) or wholesale asset-stripping (such as the Russian occupation of Eastern Germany immediately following World War 2).

The outcome of the war is for now assumed to be determinate (although this assumption will be relaxed in the section on model extensions). Specifically, it is assumed that victory depends on the ratio of the attacker’s forces to those of the defender, and the state of the offence-defence balance. The state of the offence-defence balance is represented by the parameter r, which is the ratio of attacking to defending forces needed to ensure victory. If A is the attacking nation, then its forces must be more than r times larger than those of nation B to achieve victory; otherwise it is defeated and suffers all the effects of the losing state. r thus captures the “potential physical relationship between the forces of the contested powers, A and B, at various absolute levels of arms” (Burns 1959: 358). By assumption, $r \geq 1$, an assumption that will be elaborated and defended in section 3.3.

Government

Much like the invisible management of an idealized economic firm, governments can arguably be equated with the organization which they control (the state). This approach was not used here for two reasons. Firstly, because as Moravcsik and others have noted, governments hold preferences, but states and systems cannot (1997: 518-519).[1] Secondly, the separation of states and governments allows the

[1] In a similar vein, Wendt separates the “material substrate of agency”, by which he means the physical, social and human capital composing the state, from “desire to preserve this material substrate, to survive” (1992: 402).

possibility of expanding the basic model by including domestic factors of varying sophistication.

Formally, governments make two types of decisions in the model: how to allocate the national resource endowment between force and value production, and when to declare war. In making these decisions, they are assumed to maximize present discounted value (see above) and to act in a rational manner (an assumption which will be explored at greater length in section 3.3). Lastly, governments are defined in the model by their sovereignty: their actions are entirely determined by their decisions and these decisions cannot be overridden by any other actor as long as the government's resource base remains greater than zero.

3.2 Components

We are now in a position to introduce second-order concepts which are defined in terms of primitive notions and evaluate their appropriateness as necessary.

States

A state is defined as any actor possessing a resource base, a value function and a force function, all of which are controlled by a single government.This definition is adequate for the theoretical purposes of this model, but it should be evaluated according to the criteria set out in section 1.2.

> Exhaustive: The definition is certainly exhaustive; it admits any group which possess, in lay terms, an army (force function) and an economy (value function and resource base). This definition captures all UN member states, as well as politics like the Vatican, various micro-states and also warlord-run statelets in the developing world.
>
> Exclusive: The definition as it stands is probably too broad, as it could admit any substate organizations that possess security forces capable of conducting offensive operations. In some cases this is desirable (de facto independent gureilla movements are likely to behave much like states). But in other cases it is not (well-organized transnational criminal networks may not behave similarly to states at all). In order to restrict the definition to organizations classically conceived of as "states", it would suffice to add a requirement that the resource base include geographic territory.

Analytic: The definition is clearly analytic, as each component is evaluated individually in a yes-no fashion and an overall classification is a matter of verifying that each criteria is fulfilled. This operation is itself analytic if (and only if) each criteria is analytic. Evaluating the presence of a force function, value function, resource base and government control are considered straightforward, and hence analytic, thus the definition as a whole is analytic.

The weapon space

All decisions in the model take place on an infinite Cartesian grid, restricted to the positive real numbers. This area can be thought of as a "weapon space" (Anderton 1992: 78) with each point (f_A, f_B) defining a pair of force levels for states A and B. Following political science convention, State A is placed on the horizontal axis, state B on the vertical axis. The variables f_A and f_B will be used to refer to specific force levels of each state.

Balance-of-power lines

Based on the definition of war given above, we know that for every level of force possessed by A, which will be represented by the variable f_A, there is a corresponding level of force $f_B > r \cdot f_A$, which will allow state B to attack successfully (while attacking at any lower force level will result in defeat). Mathematically,

$$f_B \begin{cases} f_B > r \cdot f_A & \text{B will win an offensive war} \\ f_B = r \cdot f_A & \text{B will fail in an offensive war} \\ f_B < r \cdot f_A & \text{B will fail in an offensive war} \end{cases}$$

r is assumed to be symmetrical and apply equally to both states, representing a system-level offence-defence balance. Some, however, have called for a dyadic offence-defence balance which may be asymmetric in some cases (Shimshoni 1993/1994). However, the model could easily be modified to include unique values of r for each state without changing the generality of its conclusions.

This relationship can also be represented graphically, in which case the line $f_B = r \cdot a$ divides the weapon space in to two regions: one including all force level combinations at which B’s attacks can succeed, and another including all combinations at which B’s attacks will be defeated. Likewise, $f_A = r \cdot f_B$ defines similar areas of victory and defeat for A. Figure 1 presents an example from B’s perspective using r set arbitrarily at 2. Figure 2 presents the same example from A’s perspective.

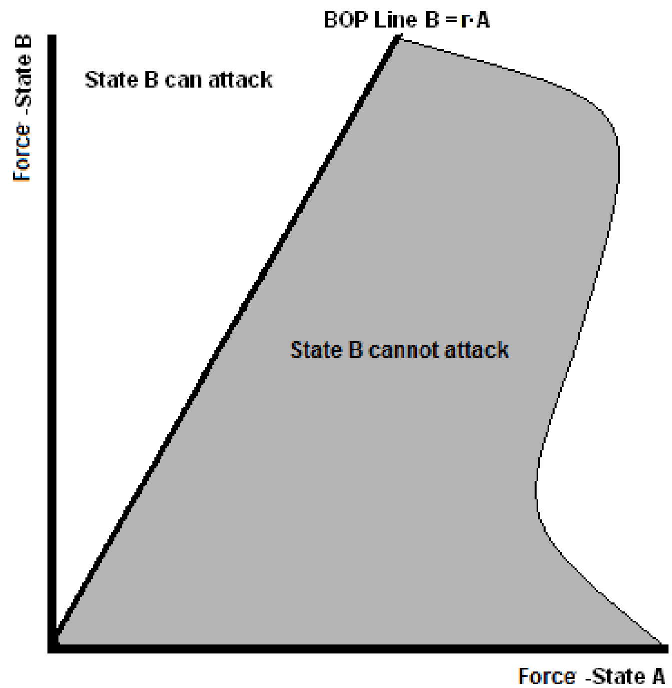

Figure 1. Balance of power lines for State B

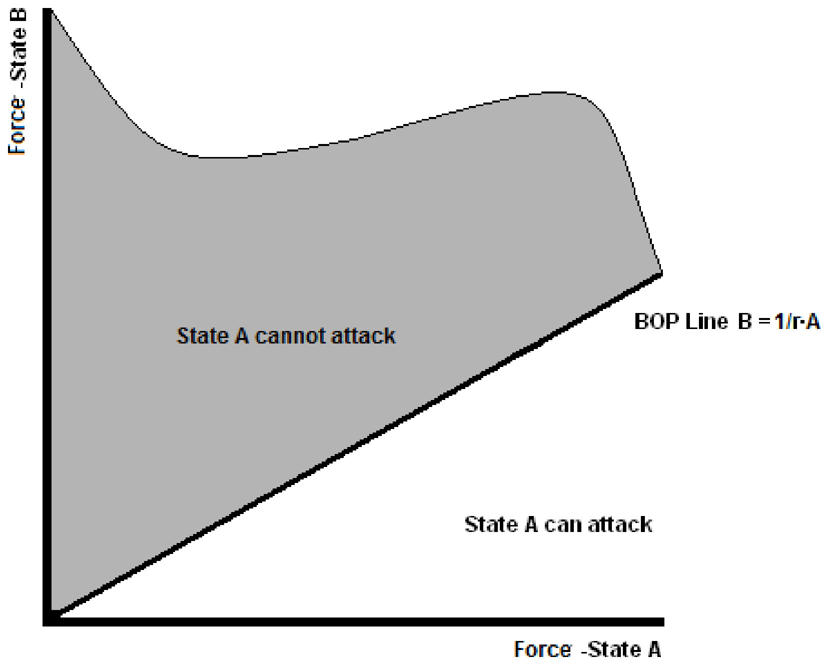

Figure 2. Balance of power lines for State A

The lines $f_A = r \cdot f_B$ and $f_B = r \cdot f_A$ are known as *balance of power* (*BOP lines*) lines, since they mark the points at which a fundamental shift in power relationships occurs. When figures 1 and 2 are combined in to a single graph, as in figure 3, the overlap of the two lines forms a line (if $r = 1$) or a cone (if $r > 1$). This area is called the *balance of power cone* (*BOP cone*), as all force combinations lying inside it are militarily stable and neither side is capable of attacking the other, thus a short run balance of power exists.

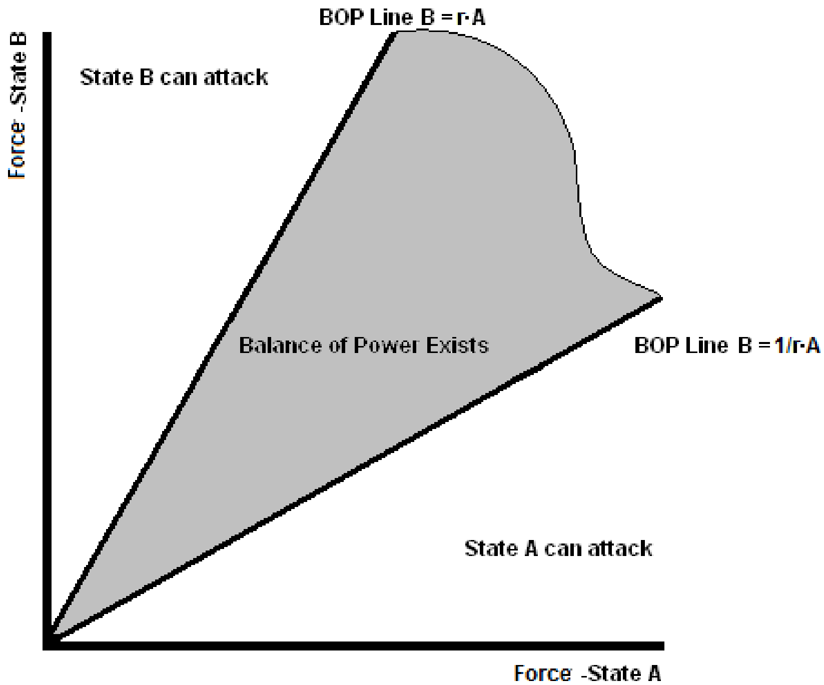

Figure 3. The balance of power cone

Burns (1959) took a similar approach to representing power relationships graphically, but chose to end the lines short of the origin, stating that "the nature of [combat] probabilities cannot be diagrammed very clearly at low levels of force" (1959: 328). Burns argument is based on surprise dominance at very small force levels (i.e. 10 ten could kill 200 if they took them by surprise at night, while the outcome of a dogfight between two squadrons of a dozen aircraft will be influenced heavily by idiosyncratic factors). Given that the Correlates of War definition of war used by political scientists requires at least 1000 battlefield deaths, concern with small scale size effects seems unnecessary. Furthermore, as section 3.3 will show, the effects of surprise have often been overestimated by analysts. Thus the model's BOP lines converge at the origin. At (0,0) there is by definition a balance of power, since $0 = r \cdot 0$ for both sides.

Desired Correlation of Forces

A correlation of forces is any point in the weapon space. The term "correlation of forces" comes from the Soviet military lexicon (Sheehan 196: 146) and was originally used to capture the full spectrum of power capabilities on which nations could be compared (i.e. hard plus soft power (Nye 2004) in all their forms, to use modern terminology). The term is used here in a narrower sense to refer only to the balance of actualized military power. This is a corruption of the original usage, but was deemed preferable to grammatical oddities such as an "uneven balance of power."

The desired correlation of forces (DCF) is a state's reaction curve in the weapon space: for every possible force level f_A, it indicates B's preferred corresponding force level f_B. That such a point exists is straightforward. Rappoport recognized this when he said:

> "For any given value of [the armaments of A] there is a value of [the armaments of B] which [B] considers consistent with her security, its [sic] sense of what she can afford, and her degree of animosity towards [A] for other reasons." (1957: 268)

That such a point is unique (i.e. only one such point exists) is also clear. A would be indifferent between multiple force levels, ceteris paribus, only if they yielded equivalent security and if force were costless, which by assumption it is not. Thus the DCF is a function. Conceptually, the DCF represents a nation's optimal arms racing strategy for all contingencies.

The precise form of the DCF is not evident a priori, and deriving its functional form is one of the main results of this paper, contained in the section on the solution to the arms racing problem.

Time

Time in the model takes places in political qualitative time, as laid out in section 1.3. However, periods are used in solving the arms racing problem in order to operationalize the model. The length of these periods is unimportant and they exist solely for mathematical convenience. Although arms racing takes place in periodized time, these periods are set within the political long run.

3.3 Assumptions

The preceding two sections have dealt essentially with questions of definition , and as has been remarked many times, definitions are neither true nor false, just more or less useful. This section addresses assumptions about the world of international relations, and as such, each assertion can be either true or false to varying degrees. As mentioned in section 1.1, sets of assumptions should be evaluated according to the accuracy of the predictions which they generate. But if a theory fails to predict accurately, the source of the errors may be indeterminate. Thus it is useful to assess the plausibility of a theory's core assumptions, which is the task of the following sections.

Rationality

The status of rational choice in political science remains controversial. It is, after all, easy to pillory rational choice approaches to international relations (e.g. "a great deal of argument about military strategy postulates 'rational action' by a kind of 'strategic man', a man who on further acquaintance reveals himself to be a university professor of unusual intellectual subtlety." (Bull quoted in Quester 1977:8)). But on a deeper level, rational choice approaches constitute a series of "methodological bets about what will prove to be productive ways to think about strategic interactions" (Lake and Powell in Lake and Powell 1999: 4).

There are a number of reasons to believe that rational choice is particularly well suited to the analysis of security issues in international relations. The first is the gravity and importance of grand strategy. Thus Machiavelli counselled rulers that: "Everyone may begin a war at his pleasure, but cannot so finish it. A prince, therefore, before engaging in any enterprise, should well measure his strength and govern himself accordingly"(Machiavelli 1998: X:I). As a result, states should devote considerably more attention to security affairs and should strive as much as possible to free security policies from partisan or bureaucratic politics and allocate large amounts of informational/analytical resources to security

(Morgenthau 1978; Waltz 1979). This should lead to behaviour which, if not perfectly rational, will at least closely approximate rational choice predictions.

A second line of attach, which complements the above reasoning, but which is independent of it, focuses not on incentives for rational state cognition, but rather on “evolutionary pressures” or selection effects”. This argument was first articulated by Waltz when he argued that:

> "To say that 'the structure selects' means simply that those who conform to accepted and successful practices more often rise to the top and are likelier to stay there. The game one has to win is defined by the structure that determines the kind of player who is likely to prosper." (Waltz 1979: 92)

Rational behaviour is, by definition, the best response to a given situation, thus rational actors will, on average and over time, outperform non-rational actors. Since the penalty for under-performance in real politik is the loss of territory and eventually political extinguishment, then a system composed of both rational and non-rational actors will over time converge towards a fully-rational system. [1]

Lastly, macro-level evidence of optimal decision-making can be found in the patterns of victory and defeat in international wars. As mentioned in the review of expected utility theory, the attacker won 70% of all wars since 1815 (Lindley and Schildkraut 2005: 1). Additionally, Mahnken listed only six cases in which the weaker power emerged victorious from a dyadic war: the 1905 Russo-Japanese war, the 1919-1920 Russo-Polish conflict, the 1965 Indo-Pakistani war, the Vietnam War, the French-Algerian War and the Soviet-Afghan War (in Handel, Lee and Walling 2003: 60). Thus it would seem that “War and use of military force can possible serve as an instrument of policy only for the initiator of war” – a key tenet of rationalist theories (UN Institute for Disarmament Research: 25).

This list is deeply flawed, and arguably none of the cases are correctly classified. In the Russo-Japanese case, Japan faced only a fraction of the Tsarist empire’s

[1] To follow Waltz in his use of domestic political analogies, similar remarks can be made about ex-Communist parties, who were forced to adapt to electoral competition or fade away in to obsolescence. The fact that many of these parties still exist is a testament to the ability of selection effects to rework even the most rigid political systems. (e.g. Ziblatt and Bizouras in Bovoki and Ishiyama 2002).

land and naval power at any time, so that it would be incorrect to dub Japan the weaker power. In fact the Japanese general staff estimated that they had a 50% chance of victory at the outset of the conflict, suggesting that they viewed the balance of power as roughly *equal* (Mahnken in Handel, Lee and Walling 2003: 66). In the Russo-Polish case, Poland was fighting not "Russia", but rather the Bolshevik controlled fragment of the country, which was itself at war with Finland, various "White" factions and an array panoply of anarchists, separatists and peasant rebels (Mawdsley 2000: *passim*, but particularly chapter 18). If anything, Poland was the stronger actor. Mahnken's inclusion of the 1965 Indo-Pakistani was is even more questionable, as the historical consensus is that Pakistan lost. Hagerty 2005: 26; McCollum 1994: E1827) The remaining three conflicts are all guerrilla wars that arguably should not be classified alongside conventional interstate conflicts. [1] In the absence of notable dyadic counterexamples, modelling interstate war as a rational endeavour is likely to be a good first approximation.

Finally, there are significant epistemological benefits inherent in the rational choice approach as a whole. As Glaser (2000) points out, in the absence of a rational model of arms racing, there is no baseline from which to judge the extent of irrational decision-making which actually occurs. Rational choice models are also very adaptable to non-optimal decision-making through the use of incomplete information, computation limitations, norms and transaction costs. This possibility of modelling non-rational decision-making coincides with the emergence of behavioural economics as a discipline, and Schelling noted that "irrationality is not hard to work in to the analysis if it is identifiable and systematic" (1984: 207). Schelling's position on rationality more broadly is worth quoting at length, as it illustrates the flexibility of rational choice as a modelling tool, and its general appropriateness for international relations:

---

[1] This point is perhaps debateable, but since this paper defines war as contest over resources, introducing guerrilla wars merely creates an exception that proves the broader rule: weaker powers cannot invariably lose conventional conflicts.

> "Whether the process has to be subtle, refined and self-conscious or crudely approximated and semi-conscious depends on whether the situation is complex and call for refined analysis, as in parliamentary strategy, or involves simple choices, such as when a child pretends not to hear a command, or when a person is asked to pick his own night to come to dinner so that he cannot excuse himself by being "busy" that night. The critical question is not whether a person is 'rational' according to any particular definition, perfectionist or merely approximate, but whether his choice is determined in large part by the situation he is in and by what we can guess about his values." (Schelling 1984: 205)

That state behaviour is determined by the external environment and state perceptions of national interest seems to be a productive methodological bet, and thus rational choice is adopted as the main approach for this paper.

Weak defensive superiority

The model assumes that the value of the offence-defence parameter, *r*, is equal to or greater than 1. This implies that the attacker must *always* outnumber the defender (by a margin which can be vanishingly small, but a margin nonetheless). This assumption runs counter to much of the offence-defence theory literature, which speaks of periods of "offence dominance" (see Levy (1984: 228) for an exception). The assumption also runs counter to a naive interpretation of offence-defence theory, which holds that clusters of notable aggressive victories in history indicate periods of offensive dominance. Finally, there are military operations manuals which typically recommend the offensive as "the surest way to achieve decisive results" (e.g. US Department of the Army 2008: A1). The assumption of (weak) defensive superiority would seem to be an unreasonable one.

This section demonstrates to the contrary that weak defensive superiority is not only a reasonable assumption, but highly probable one given the nature of military conflict. This is shown first at the abstract level of military theory, then through the principle of selective symmetry, and finally by cataloguing the practical benefits of defensive warfare on land, at sea and in the air. First however, we turn to the issue of clearly delineating offensive and defensive military conduct.

Offence-defence theory rests on two main premises: firstly, that offence and defence are separate and distinct phenomena, and secondly that they have distinct technological and doctrinal requirements (Shimshoni in Brown et al. 2004: 198). Yet this division is rarely clear-cut, and scholars have raised questions about the classification of counterattacks by the defender, as well as the status of preemptive wars. Betts goes as far as to claim "when security is defined in terms broader than protecting the near-term integrity of national sovereignty and borders, the distinction between offence and defence becomes hopelessly blurred" (1982: 142). It is thus helpful here to examine efforts by legal scholars to define aggression under international law, as lawyers are trained to seek analytic definitions (domestic crimes, for example, must be defined such that any action returns a verdict of either guilty or not guilty). Difficulties in this endeavour have coalesced around two issues: an appropriate definition of the "use of force" and determining hostile intent.

Attempts to list all warlike uses of force have been frequently overtaken by changes in the art of war and statecraft. Thus blockade and invasion had to be supplemented with the hosting of hostile guerrilla bands and bombardment launched from one state in to another (Solera 2007: 58, 64-65, 68). From the perspective of this model, these distinctions are less important, since force is an undifferentiated concept, and war as defined as the sole use in which force can be applied. Hostile intent has proven an even more difficult concept to define. Soviet negotiators successfully argued that the first use of force defined aggression during the inter-war period (Solera 2007: 36) but this overlooked the legal concept of *mens rea* or guilty intent. The notion of intent was central to the Nuremburg trials, which found Japan guilty of aggression against the Netherlands, even though the Dutch declared war on Japan, by virtue of the fact that Japanese war plans predated the Dutch declaration by several months (Olusanya 2006: 69). The question of preemptive wars can be resolved in the model by reference to the definition of war as an all-or-nothing contest. Militarily and physically, preemptive war is identical to an aggressive war, and the main difference is found in its political objectives. Since the model holds the objectives of war fixed, such concerns are assumed away so that the initiator of a pre-emptive strike is considered an attacker. Counterattacks conducted after a war starts are more nuanced, but in general the definition of the attack remains fixed from the beginning of the war to the end.

If offence and defence are separate military postures, it is natural to investigate Shimshoni's second proposition: that the technical requirements for attack and defense require very different sets of military hardware. This question is an old one, dating back to interwar disarmament conferences which attempted to ban "offensive weapons" but which were unable to arrive at even minimal consensus. There is agreement among political scientists that mobility is a technological characteristic that benefits the attacker (Levy 1984: 225), but most other attributes, such as firepower and armor have had mixed effects historically (Kahn 1962: 2; Brown in Brown et al. 2004: xv).[1]

It is also difficult to analyze the synergy which exists between seemingly defensive forces and offensive strategies. From a naive theoretical standpoint, Surface to Air Missiles (SAMs) should be classified as defensive weapons, but the use of SAMs was one of the chief enabling factors in the 1973 Egyptian attack on Israel (Luttwak 2001: 41). Other cases are relatively straightforward, as in the case of interceptors. These aircraft are fast and possess high standoff range firepower. But their armament is poorly suited to dogfighting, they are not very stealthy, and they lack the fuel capacity to "loiter" above a given area (Thorton 2007: 80). Thus interceptors are poorly suited to supporting offensive operations, either by attacking ground targets or by maintaining air superiority above the battlefield.

[1] Consider firepower, which was offence-facilitating during the Renaissance, as it allowed attackers to quickly breach fortress walls, but defence-facilitating during the First World War, as the volume of fire delivered to a battlefield became too intense for most infantry attacks to succeed.

The general solution to this question is to recognize that the offensive or defensive contributions of military hardware are always matters of degree. Artillery bombardments may support both attack and defence, but historical experience shows that artillery fire is felt more heavily by the attacker, whose forces are exposed while advancing – in contrast to the immobile and possibly entrenched forces of the defender. Thus all weapon platforms contribute to both offensive and defensive missions but do so at differential rates. It is perhaps for this reason that Soviet military doctrine defined an ideal attack ratio as 3:1 superiority in tanks, 5:1 in personnel and 9:1 in artillery (Dupuy1979: 60) – the increasing rates of superiority perhaps reflecting the higher defensive potential of infantry and artillery forces.

The advantages attributed to the attack by writers on "the principles of warfare" vary, but those used in the US Army Operations Manual (US Department of the Army 2008 - hereafter USDA) are broadly representative and will be used here. According to the operations manual the attack allows: decision, concentration, surprise and initiative (USDA 2008: A1-A3). The first point is indeed true (few objectives can be accomplished merely by awaiting the enemy's blows) but irrelevant to the relative power of attack and defence from a military perspective. The second principle, initiative, is the ability of the attacked to "force the enemy to react" and to restrict his freedom of action to undertake non-defensive operations (USDA 2008: A1-A2). Again, this principle is true but irrelevant to the overall military balance; if the defensive remains superior tactically (and the principle of initiative has no bearing on this fact) then holding an enemy to a defensive posture achieves little in the long run other than generating disproportionate losses for the attacker.[1] The principle of concentration reflects the attacker's ability to "concentrate the effects of combat power at the decisive place and time" (USDA 2008: A2). This is effectively a variant of surprise, as an anticipated concentration of forces can be opposed by an equal and offsetting

[1] The freedom to choose the field of battle is, in these circumstances, a false freedom – much like Oscar Wilde's observation that the homeless have the freedom to choose which bridge they will sleep under each night.

concentration by the defender. Thus concentration cannot exist in the absence of surprise. Surprise is indeed an inherent advantage of the offence, and in fact, surprise is arguably the *only* advantage of the offence (USDA 2008: A3). This point is conceded as generally true, but as explain in the next section, the model's assumption of full information renders surprise impossible. Thus on closer examination, the theoretical advantages of the offensive reduce to surprise, an advantage that is assumed away under this model. We turn now to the principle of selective symmetry.

The principle of selective symmetry reflects the defender's ability to imitate offensive tactics when convenient, while retaining the option of reverting to defensive tactics at any time. Consider a simple example from ancient Greece: the shock of a phalanx was greatly improved by charging; thus all pitched battles opened with a charge by the attacker.[1] Since the attacker needed to close with the defender's forces it was natural to attack via charge. Yet this did not imply that the defender was bound to wait passively. Defenders could (and generally did) counter-charge so that the momentum on both sides was equal. If for some reason the defender gained a tactical advantage from immobility (such as holding the high ground) the defender could remain in place. This second course was open only to the defender, whose options thus included all strategies available to the attacker, and strategies of a purely defensive nature. For a more modern example, consider the Battle of Kursk. Here the Soviet army prepared elaborate defensive positions, absorbed the German blitzkrieg attacks, and subsequently switched over to the offensive themselves. Note, however, that the Soviets could have adopted a purely defensive posture or met the Germans with an immediate counter-attack – and both of these options were considered by Soviet generals (Glantz and House 1999). This flexibility is inherent in the positive aim of the offensive, which requires the attacker to seek out the defender, and in so doing abandon the

[1] This runs counter to Quester's (1977: 17) claim that the loss of unit cohesion from advancing made tactical movement of any kind a hindrance during this period. This claim was unsupported by references and flatly contradict historical evidence (e.g. Catton 2006: 6-8, 17-18, 20-21, 25; Spoulding and Hoffman 1994).

advantages of the defence. We turn now to a practical consideration of those advantages in the three main theatres of combat: land, sea and air.

Military strategists are nearly unanimous in their support for the notion that "defence is, in itself and everything else being equal, the stronger form of war… attack qua attack is the weaker form of war. Therefore the side that attacks ordinarily requires a superiority, whether quantitative, qualitative or both" (Van Creveld 1991: 110-111). This recognition goes back to at least Clausewitz, who wrote: "All the advantages and all the stronger forms of combat are on the side of the defensive" (1982: 128). A few decades later and fighting a war very different from the kind envisaged by Clausewitz, Union generals such as Sherman recognized that the defender possessed a significant advantage over the attack:

> "Full 300 000 of the bravest men of the world must be killed or banished [captured] in the South before they will think of peace, and in killing them we must lose and equal or greater number, for we must be the attacking party." (Ewing 1987: 37)

The casualty differential raised by Sherman arises because defenders in a land war have many advantages over the attackers: superior knowledge of local terrain, shorter supply lines (recall that longer supply lines create "virtual" attrition for the attacker as combat troops are diverted to police functions in rear areas (Luttwak 2001: 203)), the benefits of entrenched immobility (an advantage which gave rise to the 3:1 rule in the first place) and generally the sympathies of the local population. To these strategic advantages one can add biological evidence that humans are hard-wired to fight harder when defending areas they regard as their homes (Carré et al. 2006). Significantly, almost all of these advantages will increase as the defender is pushed farther in to his homeland. The defender's strategies thus include all those open to the attacker and more, which guarantees at least equality with the attacker. Thus it is rightly "a military truism that… the tactical defensive is often the superior position" (Possony and Pournelle 1970:183).

Naval warfare would seem to be a strange environment in which to assume a defensive advantage, as combat takes place on a featureless plane. Yet for both tactical and strategic reasons, even at sea "The offence undertakes certain risks and disadvantages in order to reach and destroy the enemy; the defence, so long as it remains such... holds on to a careful, well-ordered position, and avails itself of the exposure to which the attack submits himself" (Mahan 1892: 6) Up until the emergence of the aircraft carrier, approaching an enemy fleet meant that the attacking admiral sacrificed at least half of his ships' firepower, while enemy vessels remained at full efficiency. Even in an era of aircraft carriers and cruise missiles, dogfights which occur close to friendly carrier battlegroups (i.e. defensive ones) benefit from improved electronic warfare and radar coverage, as well as supportive fire from AEGIS cruisers. Lastly. Navies defending a nation's shoreline benefit in several ways relative to attackers. Defending commanders will have superior knowledge of local geography and currents (Mahan 1892: 27, Lindberg and Todd 2002), access to safe harbours and support from coastal batteries or land based aircraft (Brodie 1944: 286; Friedman in Harding 2005: 260-261). Historically, navies designed for close-to-home operations (green water navies) were more combat capable than their blue water opponents. Wilhelmine Germany produced dreadnoughts with thicker armour than their British counterparts) since German ships did not devote as much space to tolerable crew compartments or large coal reserves (Padfield 1974: 104. The opposite applied to the Russian navy, whose ships had thinner armour relative to the Japanese due to the need to transfer over vast inter-oceanic distances. Thus while naval combat is not as defence-dominant as land combat, there is still reason to believe that if either side holds an advantage, it is the defender.

Air warfare, much like war at sea, appears to be an unlikely candidate for defensive advantage, as combat takes place in an empty three dimensional space. It is true that nature provides little to distinguish between friendly and hostile airspace (although arguably defenders will have greater knowledge of local weather patterns), but air war infrastructure does create a meaningful tactical distinction. The defenders in air combat can rely on anti-aircraft defences (often stationary weapons, but also barrage balloons or searchlights or radar, depending on the era in question) which increase the efficiency of defending aircraft over attackers. Defensive air operations also receive the tactical benefit of reduced fuel consumption, which leaves a greater margin available for maneuver, climbing to superior altitudes or loitering until a tactical opportunity presents itself (Zhang 2002: 117). Lastly, air combat which takes place over friendly territory allows downed pilots to be rescued and returned to service, which not only reduces loss of highly-trained manpower, but leads to the accumulation of more experienced pilots. The latter factor proved particularly decisive during the battle of Britain, for instance (James 2000: 69). Finally, one could argue that at the level of force construction, equal investments by the attacker and the defender will leave the defender with air superiority, since the attacker must divide resources between both bombers (either strategic bombers or close air support aircraft) and escorts, while the defender can focus solely on interceptors and fighter aircraft.

Full Information

The model assumes full information for both states, including awareness of their adversary's fully-informed status and so on, ad infinitum.[1] This section will defend the assumption of full information, both in general (at the level of grand strategy) and concretely (in terms of military surprise attacks).

Assumptions of full information, or "battlespace transparency" (Cohen 1996: 44) in military parlence are common in exploratory modelling. However, there are many who argue that uncertainty is fundamental to the nature, and hence the study, of international relations. Clausewitz famously declared that "[A] great part of the information obtained in war is contradictory, a still greater part is false and by far the greatest part of all is of a doubtful character" (1982: 162). While a UN training document, for instance, emphasized that "dealing with international structural conditions of political and economic matters means, above all *dealing with uncertainty*. No one will ever grasp world politics to its fullest extent, thereby eliminating all uncertainty" (Frei and Ruloff 1989: 3, emphasis in the

[1] But not, of course, the strategies that their opponents will adopt.

original). Academics have also attributed great importance to uncertainty (e.g. Cline 1980: 12; Fearon 1995 *passim*) and even to changing levels of uncertainty (e.g. Singer, Bremer and Stuckey in Russet 1972: 23-27, 45). Concern over incorrect information underlies the mistake theories of war outlined in chapter 2, along with signalling and information-centric theories. It is thus incumbent on the modeller to justify such an extreme assumption.

On a purely abstract level, many arguments similar to those advanced for state rationality may be made here as well. Epistemologically, full information models - whether empirically accurate or not - allow scholars to diagnose the extent to which imperfect information matters in international conflict. Until we have accurate predictions for the full information case, it is difficult to make meaningful statements about the role of uncertainty. More practically, evolutionary/selection effects also operate on states' information gathering and analysis operations. Thus economic theory

> "tends to minimize the importance of perceptual differences, among other reasons because incorrect beliefs are normally unprofitable and hence subject to adjustment by experience. In conflict situations as well, contenders do presumably learn from experience. The school of actual struggle teaches parties to readjust their perceptions to more realistic level." (Hirshleifer in Hartley and Sandler 1995: 175)

Starting from a pure information case is simpler methodologically, and allows for more precise predictions, but imperfect information and uncertainty are also perfectly compatible with a rational choice perspective. Expected utility theory, after all, emerged through the study of how a rational gambler would allocate bets across gaming opportunities.

From a military perspective, the most important property of the full-information case is that surprise is impossible. Yet political scientists and military strategists have devoted an enormous amount of attention to surprise attacks, mostly how they occur, but also their impact on the subsequent military struggle. Again, it is incumbent on the modeller to justify the use of a seemingly counterintuitive modelling strategy. The first step is, of course, to define surprise. Academics have typically recognized three kinds of surprise (Knorr and Morgan in Knorr and

Morgan 1984: 2): unexpected war initiation (as in China's entry to the Korean War), unexpected extension to a new theatre (the Inchon landings during Korea), or unexpected use of a new mode of war, either technological or doctrinal (such as, arguably, allied dam bombing attacks during the later stages of that conflict (Futrell et al. 1961: 176, 626)). Within each category, surprise occurs if: one, the attacker's actions are not consistent with the defender's expectations and two, there is a failure of warning that this is the case, leading to three, the victim fails to meet the danger adequately (Kam 2004: 8).

If achieved, surprise is held to offer a number of benefits: lower casualty ratios (from 5:1 in favour of the defender to 1:1 with surprise according to Betts (1982: 5)), surprise acts as a force multiplier (Hybel 1986: 25, 152; Betts 1982: 5), surprise increases the speed of victories (Knorr and Morgran in Knorr and Morgan 1984: 11) and, by paralyzing decision-making capabilities of the enemy "surprise…. is the suspension, if only brief, if only partial of the entire predicament of strategy." (Luttwak 2001: 41). Given these advantages, it is perhaps predictable that "most wars in recent memory began by surprise attack" (Betts 1982:3). Surprise is held to be easily achieved by most international relations scholars and Kam summarized the views of many when he concluded that: "it is at best very difficult to prevent surprise attack" (2004: 229). The reason for this pessimism is not difficult to locate:

> "The conditions necessary for the defender to be victimized are not really unusual at all - ambiguous information amidst noise, secrecy and deception; preconceptions and expectations somewhat at variance with reality; organizational barriers to accurate perception and effective response; political constraints on what a government can afford to see and do. They are very much part of the daily realities of foreign policy decision-making." (Knorr and Morgan in Knorr and Morgan 1984: 240)

In such conditions, even successful warning can be indistinguishable from failure: "If the defender recognizes the warning and responds in time with defensive preparations, the attacker may cancel the operation…The victim's intelligence is at the mercy of the attacker's option to change his plans" (Betts 1982: 95) which leads to "alert fatigue", and eventually a successful surprise attack.

However, there are many reasons to believe that the studies quoted above over-state the importance of surprise, as well as the ease of obtaining it. Clausewitz, for one, acknowledged the importance of surprise, but dismissed it as a rare and ephemeral factor in war (1982: 213, 270-272). In fact, Clausewitz went so far as to claim that surprise "seldom succeeds to a *remarkable* degree" (1982: 270, emphasis in the original) and that *truly successful* surprise attacks owed their success to favourable circumstances unknown to the attacker beforehand (1982: 270).[1] Indeed, Kam's list of 11 "major" 20th-century surprise attacks included only 4 involving great powers (2004: 3). More importantly, the fact that most wars begin with surprise attacks,[2] tells us that surprise alone cannot be decisive, as the wars of recent memory include a wide range of outcomes for the attacker. In fact, military historian John Keegan has argued that "it is an error to think that surprise by itself determines more than the outcome of the first engagement; thereafter other factors… come in to play." (2003: 42)

Keegan's thesis deserves further consideration, as his book *Intelligence in War* presents a number of cases from recent military history in which surprise, facilitated by total intelligence domination, played only a modest role in battlefield results. Two cases in particular deserve special attention, as they constitute Ecksteinian (1975) "crucial cases" in which perfect intelligence allowed for total surprise of the adversary: the battle of Crete in 1941 and the battle of Midway in 1942. In the case of Crete, allied codebreakers had access to all of the Luftwaffe's transmissions, allowing full foreknowledge of the German order of battle, landing sites, convoy timetables and real-time tactical developments (Keegan 2003: 192-196). Despite these advantages, and the risks inherent in the German airbone attack, the Allies failed to defeat the numerically weak German forces. The battle of Midway is an even more compelling example. US codebreakers had routinely decrypted Japanese transmissions, leading to perfect

[1] Thus Clausewitz would probably have attributed the success of both China's initial Korean offensives and the UN counterattack at Inchon to the dangerous overextension of the victim's forces at the time of the attack, rather than surprise in and of itself.

[2] Kam (2004: 4) lists only the 1948 Arab-Israeli war, the 1965 Indo-Pakistani war and the 1967war between Jordan and Israel.

foreknowledge of the Japanese order of battle and the target of their attack. Yet in the course of the engagement, just as Clausewitz would have predicted, the fog of war proved to be the most important factor in determining tactical outcomes. The success of American forces hinged almost entirely on contingent factors such as the timing of each side's airstrikes, visual acquisition of the Japanese fleet by air squadron leaders, and poor decision-making on the part of Japanese officers (Keegan 2003: 250, 373-383). Thus for every Barbarossa (whose success was arguably due to Stalin's poor force deployment patterns (Suvorov 1984; Pleshakov, 2005)) there is a Pearl Harbour (which failed to achieve a crippling blow against the American Pacific Fleet), and for every Pearl Harbour there is a Port Arthur (a surprise attack which failed to achieve even minimal damage despite ideal conditions). It is thus entirely defensible to conclude that surprise "…can only work through strength" (Kahn 1991: 91).

Resource and production constraints

States are assumed to be limited in the rate at which they can convert resources towards force. This reflects the imperfect ability of civilian infrastructure to switch over to military production (Brawley 2004). This is captured in the model by the parameter η, which limits an increase of resources devoted by force to a fraction of the state's total resource base. Thus if η = 10% and current force spending consumes 15% of a state's resource value, in the next period military spending could be increased to a maximum of 25%. In the period after that, 35%, and so on. Demobilization, on the other hand, is assumed to be instantaneous. This is an assumption of convenience, and could be changed without affecting the model's conclusions, as rapid demobilization takes place only in the aftermath of military victory over one's adversary. η is converted into force when used graphically, so that $\eta_B = f_B(s_{fB} + S_B \cdot \eta)$.

Production of military goods is also held to take time, such that force production allocated in period t is not available until period t+1. Importantly, since full information is limited to the present period, states cannot observe increases in force inventories until they enter the state's force stock at t+1. This raises a number of important strategic considerations, which are dealt with in the results section below.

3.4 Results

The war initiation decision problem: parameters and solution

The war initiation problem in the model is based on the simple expected utility calculus proposed by Bueno de Mesquita (1981), in which states compare the expected utility of fighting with the expected utility of peace, and choose war if it offers a higher payoff. Following the examples of Powell (1993), Skaperdas and Syropoulos (1996) and Garfinkle and Skaperdas (2000), state decision-making is dynamic and extends over an infinite time-horizon. States thus consider both the immediate impact of war, and also its long-run effects, which are converted into present value through the state's discount rate.

Unless otherwise noted, states A and B are assumed to be identical in the form of their force and value functions, size of resource base and production constraints. Unless otherwise specified, all calculations are done from the perspective of State B.

Notation for this section and subsequent ones follows the useage below, a copy of which can be found as an appendix:

$_A$	Subscript A denotes state A
$_B$	Subscript B denotes state B
$_t$	Subscript t denotes an arbitrary time period. Superscript t is "to the exponent of t."
*	a superscript asterix represents the equilibrium value of a variable
S	a state's resource base
s	any fraction of a state's resource base
s_f	the quantity of a state's resource fed in to the force function
δ	the discount rate
v(x)	the value function
f(x)	the force function
r	the minimum ratio of attacking to defending forces at which the attacker will be defeated

p the fraction of a state's resource base that is transferred to the victor after war.

η the maximum increase in force that a state can produce in a single period

Thus s_{fB}^*, for example, is the equilibrium level of resources spent by state B on force and v_{Bt} is the value function of State B in period t.

The general form of a state's value function over an infinite time horizon is given by

$$\Sigma\, v_{Bt}\, (S_B - s_{fB}) \cdot \delta^t$$

This equation says simply that a state's discounted present value is equal to the value produced in each period, deflated by the discount rate for that period. The value produced in each period is in turn equal to the value function's output from the nation's full resource base minus resources allocated to force.

Suppose state B chooses perpetual peace at some equilibrium force level s_{fB}*, then state B's discounted present value of its infinite horizon value stream is given by the equation:

$$\Sigma\, v_{Bt}\, (S_B - s_{fB}^*) \cdot \delta^t$$

Where Σ sums over an infinite time horizon t from t= 1 to t= ∞. Applying the rules of infinite series allows us to remove the discount term outside of the summation and we have:

$$\frac{1}{1-\delta} \cdot \Sigma\, v_{Bt}\, (S_B - s_{fB}^*)$$

Since S_B is fixed while s_{fB}^* is a constant by definition, the equation yields a constant. The equation increases (decreases) if the resource base grows (shrinks) or if military spending grows (shrinks).[1]

The value calculations for war are slightly more complex. Recall that war under the basic model is determinate, in which case it is clearly irrational to attack at force levels for which $f_B \leq r \cdot f_A$, as defeat is guaranteed and the state's value

[1] Technically changes in the discount rate could also influence the result, but model parameters such as discount rates are almost always assumed to be fixed.

stream is reduced to 0. Thus for $f_B \leq r \cdot f_A$, peace is the rational response (at least from state B's perspective).

If, on the other hand $f_B > r \cdot f_A$, a state can attack successfully and seize the fraction *p* of its adversary's resource base. Additionally, by eliminating its adversary from the international system, the state can reduce its force investment to zero in all future periods. Note that the importance of this "peace dividend" depends on the size of the victorious state's military budget relative to the size of its resource base (s_{fB}^{*}/S_B), so that the more hostile the pre-war situation, the more important the peace dividend becomes. This be can represented mathematically as:

$$\frac{1}{1-\delta} \cdot \Sigma\, v_{Bt}\, (S_B + p \cdot S_A)$$

Comparing this equation to the peace equation derived previously, it is clear that the post-victory value stream is strictly higher than the peace stream. This holds even if p = 0, since the elimination of State A allows B to reduce its force spending to zero. Thus if a state ever possesses the ability to conduct a successful offensive war, it is rational to do so.

The logic above is, of course, vulnerable to a Fearon style critique. Due to the destructive nature of war (if $p < 1$, war is a negative sum game), rational states have incentives to avoid conflict through a negotiated settlement that bypasses the transaction costs of fighting. Yet in this this model, Pareto-optimal contracts are rare due to the peace dividend. This occurs because State A must offer State B *more* than the fraction of resources it would gain by fighting, with the extent of these extra resources matching the value of the peace dividend for State B.[1] Depending on the exact values of p, s_{fB}^{*}/S_B and the post-transfer value of s_{ft}* pareto optimal contracts are not guaranteed to exist, contrary to Fearon's (1995) approach.

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[2] State A could, of course, promise to reduce its armed forces, but this raises contracting issues as outlined in the next paragraph.

In the event that Pareto optimal contracts exist, the inclusion of sovereignty in the definition of governments renders all negotiation problematic, as recognized by Powell (2006) and many writers on the importance of anarchy. If B was capable of conquering A at the existing correlation of forces, then it will remain capable of doing so after A reduces its resource base, force investment, or both. Thus B has no incentive to honour its agreement. Even if A reduces its armed forces to 0, B would prefer to accept a resource transfer, then renege on its commitment in the following period and conquer A. Such treachery is in fact highly profitable for B, since resources transferred voluntarily are not subject to the destruction of war. Thus if war is a feasible policy option for B, it is inevitable. Thus for $f_B > r \cdot f_A$ (or $f_A > r \cdot f_B$), war initiation is inevitable.

The arms race decision problem: parameters and solution

Given our solution to the war initiation problem, we are now in a position to determine how states should optimally conduct arms races. The first step in this process is to derive the form of the state's DCF. It will become clear that security-focused states behave differently from those attempting conquest, so the DCFs are derived separately in each case. Note that while DCFs are drawn across the entire weapons space for convenience, they do not exist outside the BOP cone, since for those correlations of forces, one side will simply attack the other in the short run. Thus it is meaningless to speak of a DCF which is defined over the political long run.

Within the balance of power cone, neither side can successfully attack the other in the short run. However, both sides must be concerned with the productive potential of their adversary. Thus to maintain an acceptable long-run level of security, a state must balance against both current enemy capabilities and also potential future production. Since the model assumes one period lags, the amount of future production which must be anticipated is equal to η. Mathematically, the most efficient security-preserving DCF line is given by:

$$f_B = \underline{f_A} + \underline{\eta_A}$$

r r

This formula is straightforward and represents B's DCF as the sum of two components. The first consists of the forces necessary to defend against A's current force inventory, while the second is the quantity of force necessary to offset one period of force production by A. This second component is necessary to prevent the emergence of a "window of vulnerability" due to force building programs by A that are unmatched at the time of their initiation. A's calculations produce an identical result for a security-preserving DCF. When both DCFs are graphed together, as on figure 4, it is clear that an equilibrium exists at $f_A = f_B = f^*$. Thus f* constitutes a Nash equilibrium for both states. The precise numerical value for f* is given by:

$$f_B = \frac{f_A}{r} + \frac{\eta_A}{r}$$

$$f_A = \frac{f_A}{r} + \frac{\eta_A}{r} \qquad \text{(in equilibrium } f_B = f_A\text{)}$$

$$r \cdot f_A = f_A + \eta_A$$

$$r \cdot f_A - f_A = \eta_A$$

$$(r-1) \cdot f_A = \eta_A$$

$$f_A = \frac{\eta_A}{(r-1)}$$

And by symmetry in the equilibrium, f_B takes on the same value. Note that if η or r differed between both states, an equilibrium f* would still exist, but at unequal force levels for A and B.

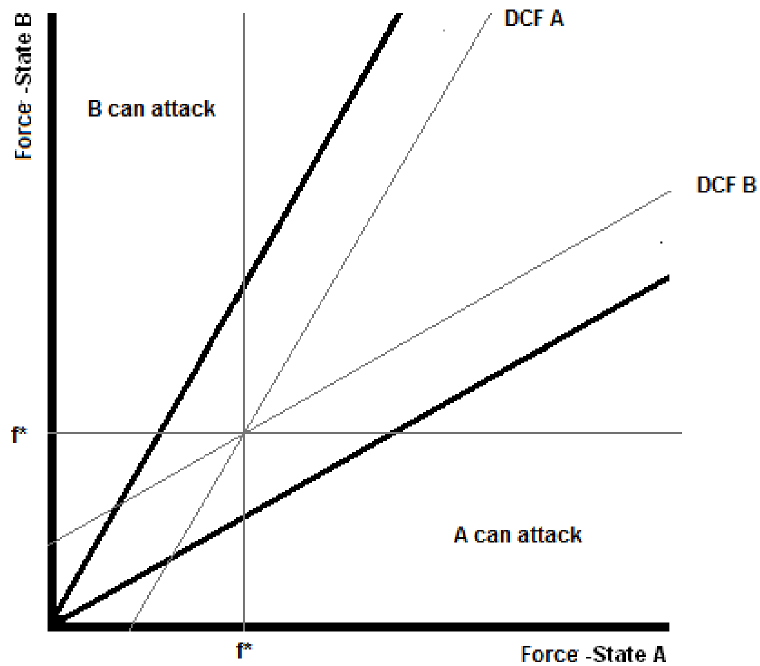

Figure 4. Security-preserving DCFs

The assertion that f* is a Nash equilibrium is proved below, but first it is important to investigate the existence conditions for f*. In the special case that r=1, for example, a single value for f* exists in which both states devote *all* of their resources to force, as maximum spending is the sole guarantee of continued existence. Yet with 100% of resources devoted to force, value production in all periods is zero, and states are indifferent between continued existence or dissolution.

More generally, the existence of f* is guaranteed for all $r \geq 1$. For values of r that are small relative to S_A and S_B, a stable equilibrium still exists, but the calculations of both sides are slightly different. If r is small relative to resource endowments, the value of f* will be very high, and f*+ η will exceed the total resource endowment of either state and is thus unattainable. Instead of hedging against the adversary's production capacity, states hedge against the adversary's total resource base. This requires B to hold a force inventory of $f(S_A) / r$. At this level, even if A devotes its entire resource base to force, B remains secure. This scenario is illustrated in figure 5, below, but in general this paper concentrates on the “interior solutions” of the type illustrated in figure 4, rather than “corner solutions” of the kind illustrated below.

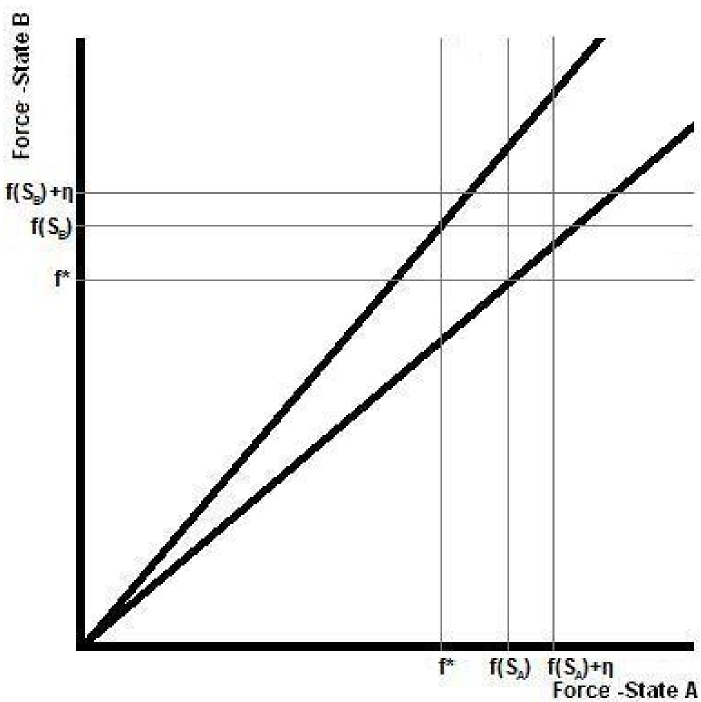

Figure 5. Balancing at high force levels

Having established the existence of f* for all r ≥ 1, it is necessary to prove that r is a Nash equilibrium for both parties. This will be done by showing that if state A is following the DCF outlined above, then state B cannot improve its value consumption by adopting any other strategy. This proof will proceed by cases, below.

Suppose that both nations start at f*. Now suppose that B reduces its force inventory below f*. This will allow A to increase its forces in the following period and successfully attack B, reducing B’s future value income to zero. Thus holding a force inventory below f* is irrational if your opponent is holding f*.

Attempting an arms race starting from f* is also futile. Suppose that again both states begin at f*, and that B increases its force inventory. If A pursues the strategy outlined above, then B's first increase in arms will place the correlation of forces at $B = r \cdot A$, but from that point on, both sides will increase their armaments in such a way that A hold B's forces at the uppermost balance of power line by following his DCF. Figure 6 illustrates this scenario, and after the initial shift in the correlation of forces in favour of B, A is able to maintain a balance of power until B has fully exhausted its resources. Such an arms race is unprofitable for B and will thus not be attempted.

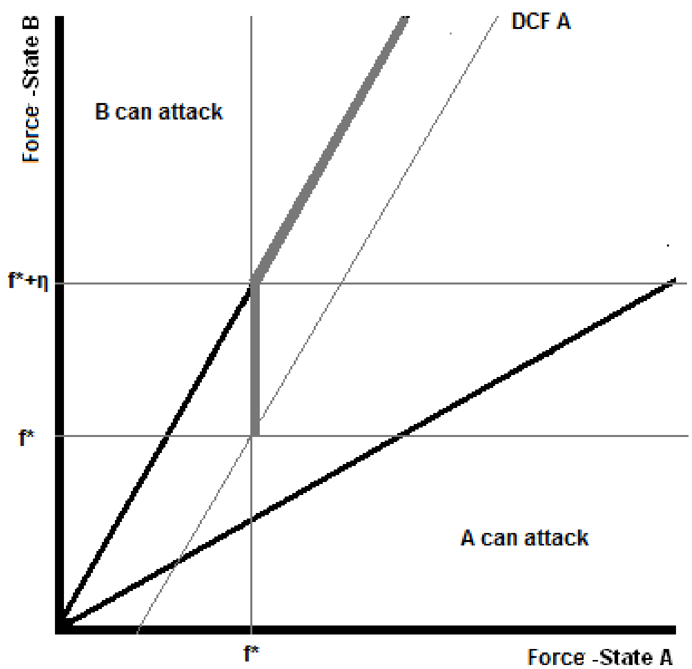

Figure 6. Futile offensive arms race

Next suppose that state A only is at f* and that B's force inventory places it somewhere within the BOP cone. Two scenarios exist. If State B is above f*, then state A will increase its forces in the next period to prevent itself from being attacked. Since both sides have equal production capacity, if A and B both increase their force inventories by the maximum possible amount, this will merely bring the correlation of forces closer to 1:1, which is by definition within the BOP cone if the starting point is inside the BOP cone as well. If A alone increases its forces according to the DCF rule $f_B = \frac{f_A}{r} + \frac{\eta_A}{r}$, this will again merely move both sides closer to equality. In either case, B gains nothing from holding higher force inventories, either in terms of security or offensive opportunities. Thus B's strategy is inferior to f*.

Lastly, suppose that A is at f* and B is holding f', a lower level of force than f*. In this case, A can increase its forces by η in the next period, moving the correlation of forces outside the balance of power cone and allowing for a successful attack on B, as shown in figure 7 below. Thus holding force inventories below f* is irrational.

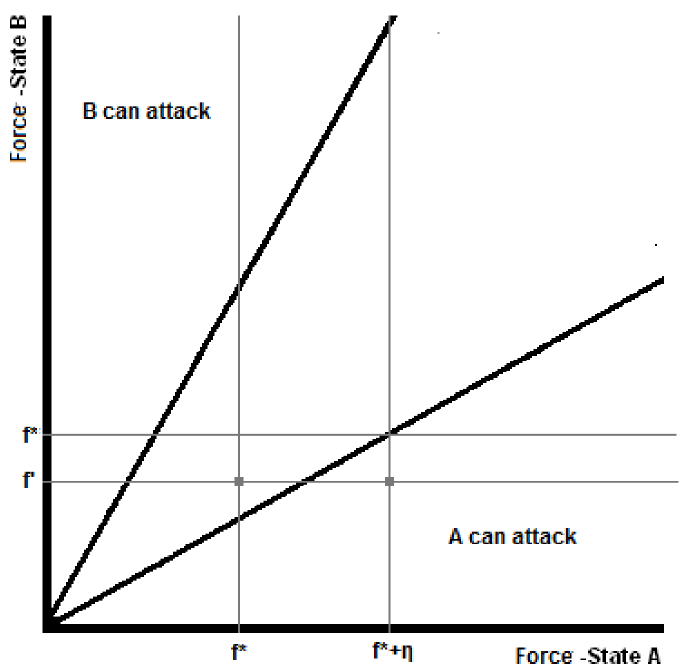

Figure 7. Low force inventories

Thus in all cases, holding a force inventory of f* is a rational response to f* held by one's opponent. Thus f* and the DCF supporting it constitute a rational defensive Nash equilibrium.

The above scenarios dealt primarily with defensive arms racing, and the DCF was repeatedly characterized as the most efficient security preserving reaction curve. This focus on security is justified by the fact that symmetrical actors cannot win offensive arms races against one another. This is guaranteed by the assumption that $r \geq 1$ and equal production capacities $\eta_A = \eta_B$, which implies that from any correlation of forces which falls within the BOP cone, neither state can outbuild the other. In fact, the possibility of an offensive arms race can occur only if the resource endowment of one state is significantly larger than the other.[1] Specifically, for B to win an offensive arms race against A, $f(S_B) > r \cdot f(S_A)$. Since f(S) is subject to diminishing marginal returns, this implies that the above inequality is a very demanding condition.

Suppose that $f(S_B) > r \cdot f(S_A)$. Starting from the equilibrium point f*, state A matches state B's buildup by following its DCF. During this competitive buildup, B's forces expand faster than A's, since $r > 1$ but the correlation of forces remains within the BOP cone. Finally, State A is reduced to spending all of its endowment on force production and cannot expand its military inventory any further. B now begins to shift the correlation of forces in its favour, and as soon as the correlation of forces leaves the BOP cone, B initiates war and defeats A. The time path of such an arms race is illustrated in figure 8, below, with the thick grey line representing changes in the correlation of forces.

[1] Or alternatively, if there is imperfect information about the size of state resource endowments.

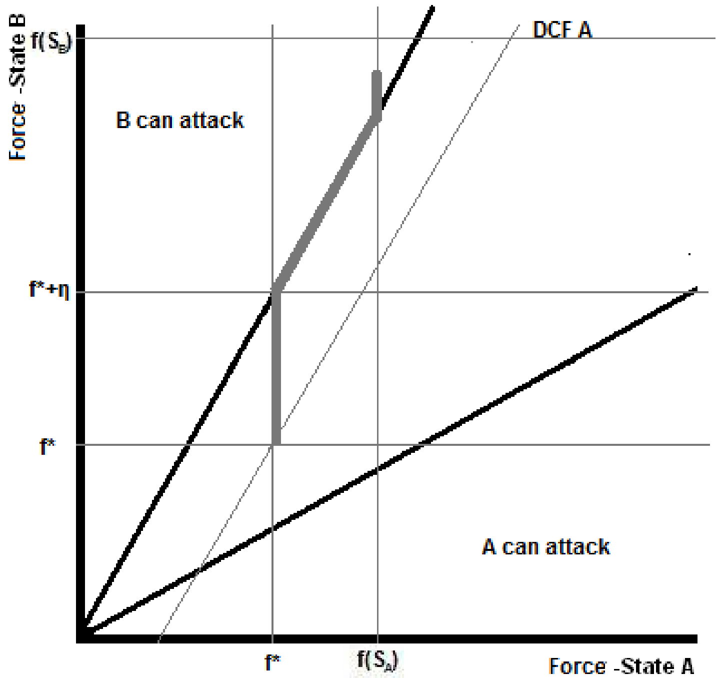

Figure 8. Successful offensive arms race

Comparative Statics

This section briefly explores the comparative statics of the model – changing one parameter or variable and deducing what changes in the equilibrium values of f* occur, and whether either side gains an incentive to begin an offensive arms race. The shocks considered in this section are: changes in the offence-defence balance and growth of either nation's resource endowment.

Shifts in the offence-defence balance, as captured by the parameter r, will result in a shift of f* to a higher or lower value, depending on the direction in which r changes. If the defensive advantage increase (r rises), then the formula for $f_B = \frac{f_A}{r} + \frac{\eta}{r}$ predicts that f* will fall. By the same token, a fall in r will increase the value of f* for both nations. All shocks to r, either positive or negative, will shift both the slope and intercept of the DCF, as illustrated in figure 9 for the case of r decreasing.

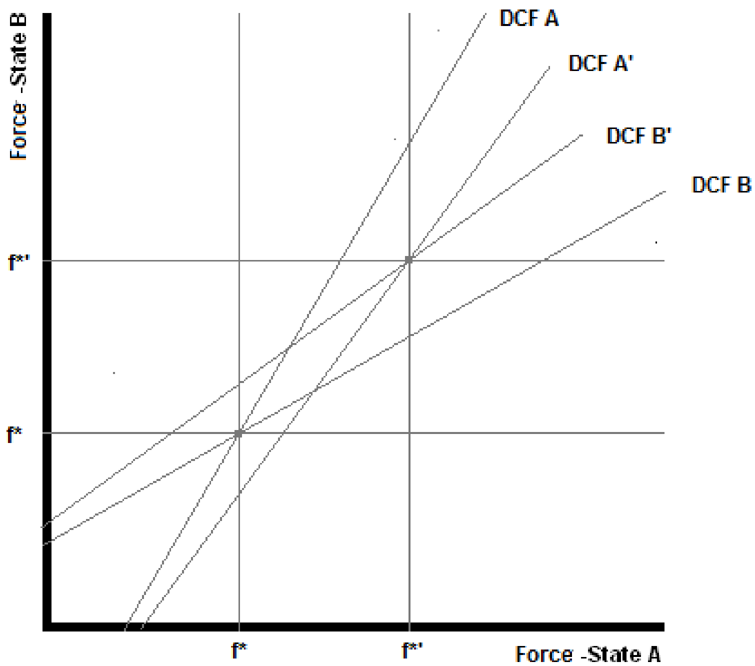

Figure 9. Shift from f* to f*’ due to a decrease in r

Growth over the very long run has complex effects depending on which side grows and by how much. The most important point is differential growth rates between A and B, which can trigger offensive arms races if either party’s resource endowment grows large enough to permit a successful arms race. This occurs whenever $f(S_A) > r \cdot f(S_B)$ or vice versa. Graphically this occurs if lines drawn from $f(S_A)$ and $f(S_B)$ intersect outside of the BOP cone.

Marginal growth in national resource endowments triggers changes in f*, but does so indirectly though changes in η. If B’s resources grow, while A’s resource base remains unchanged, B would prefer to devote all additional resources to value production while maintaining force levels at f*. However, since the growth of S_B also increases the value of η_B, A feels threatened by the productive potential of B’s larger economy and increases its forces according to the DCF. Since $f^* = \eta_B/(r-1)$ and $\eta_B' > \eta_B$, the DCF shifts outwards, resulting in a higher level of f*. More specifically, suppose that g=3% and r=2. Then given that $f^* = \eta_B'/(r-1)$ and η_B' is 3% higher than η_B, f*’ will be 3%/2= 1.5% higher.

If both countries grow at once, the result is slightly more complicated. However, a general formula for marginal growth in f*, assuming again that neither country becomes capable of winning an offensive arms race is (assuming S_A grows at rate g_A and S_B grows at rate g_B) $\Delta f^* = (g_A + g_B)/(r-1)$.[1] This can be derived from decomposing the change in f* by each country's production capacity in turn, the calculations for which are omitted to save space. This equation suggests that an "arms walk" is characterized by increases in total dyadic military spending that are lower than combined dyadic economic growth, with the degree of difference being conditional on the degree of defensive advantage.

Extensions

The basic model presented above can be extended in a number of directions by relaxing the model's core assumptions or by adding a new element (such as domestic factors or expanding the number of states to a multipolar system). This section will consider the ramifications of introducing probabilistic war in to the model, and sketch out the implications of this move in an informal manner.

States' value calculations are unchanged for perpetual peace, but take on a new format for war. Assume that victory in war is determined by some contest success function C, which assigns probability c of victory to the attacker and probability 1-c of defeat. As before, the defeated party transfers a proportion p of its resource base to the attacker and is removed from the international system. The exact functional form of C is not important, except that it systematically favour the defensive and that the degree of defence dominance be captured by a single parameter r.

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[1] Where Δ stands for "change in." Technically, the exact formula is $((1+g_A)*(1+g_B))/(r-1)$. For small values of g_A and g_B, this formula is approximated very well by the one given above. In proposing this approximation, we are following standard econometric practice for growth economics (e.g. Acemoglu 2006).

Consider first the war initiation problem. The present-discounted value of perpetual peace remains the same as in the previous model. The value of initiating a war is now given by:

$$\frac{1}{1-\delta} \cdot \Sigma\, c \cdot v_{Bt}\,(S_B + p \cdot S_A) + \frac{1}{1-\delta} \cdot (1\text{-}c) \cdot \Sigma\, 0$$

$$\frac{c}{1-\delta} \cdot \Sigma\, v_{Bt}\,(S_B + p \cdot S_A)$$

Thus in deciding whether to initiate a war, a state compares $(c/1-\delta) \cdot \Sigma\, v_{Bt}\,(S_B + p \cdot S_A)$ to $(1/1-\delta)\, \Sigma\, v_{Bt}\,(S_B\text{-}s_f{}^*)$, initiating war if :

$$\frac{c}{1-\delta} \cdot \Sigma\, v_{Bt}\,(S_B + p \cdot S_A) > \frac{1}{1-\delta} \cdot \Sigma\, v_{Bt}\,(S_B\text{-}s_f{}^*)$$

$$c > \frac{\Sigma\, v_{Bt}\,(S_B\text{-}s_f{}^*)}{\Sigma\, v_{Bt}\,(S_B + p \cdot S_A)}$$

In other words, if the probability of victory exceeds the ratio of the peacetime value stream to the victorious war value stream, a state should rationally declare war.

As we shall see, the war initiation problem is slightly more complex than it first appears, but the calculations above allow us to establish a "weak BOP cone." This cone contains all correlations of force at which initiating war is irrational for either side in the short run. Thus was will not occur within the cone, except under exceptional circumstances. At the same time, war is not, however, guaranteed to occur outside of it.

The arms race decision problem illustrates this novel development. Suppose that a state is capable of outbuilding its adversary and pushing the correlation of forces deeply in to its zone of dominance. Should it attack as soon as the correlation of forces leaves the weak BOP cone? The answer here is generally no. States may be able to improve their expected value consumption by accumulating a large margin of superiority before going to war. Each additional period spent accumulating force beyond the minimum necessary level will tradeoff greater probability of victory against delaying the fruits of conquest. Mathematically this problem is captured by:

$$\Sigma\, v_{Bi}\,(S_B - s_{fi}) \cdot \delta^i + \frac{c \cdot \delta^t}{1-\delta} \cdot \Sigma\, v_{Bt}\,(S_B + p \cdot S_A) \quad \text{where } 0 < i < t = i + 1$$

The first term captures the increased force production during the arms race period, which produces lower value than the peacetime equilibrium of $s_f=s_{f^*}$. The second term represents the expected benefits of war initiation, discounted by the additional delay to reach an acceptable level of superiority. States maximize this function by choosing t, the number of periods the arms race will last. The mathematics involved are complex and the above equation will not be solved here. We can, however, make some general statements about arms racing under conditions of probabilistic war. The expected value stream in the equation above decreases if r increases (this is the "dampening" effect on arms races from defensive superiority(Gray 197: 43)), if p decreases (this follows predictions by many liberal theorists that arms racing become irrelevant as conquest becomes less attractive (e.g. Brooks 1999: 648)) or if states become more patient through lower discount rates (this is the dark side of the "shadow of the future" as noted in Powell 1993).

Lastly, a special case exists for wars which can occur within the balance of power cone. These are preventive wars, in which one side anticipates that the correlation of forces will deteriorate in the future, leading to war at the opponent's preferred correlation of forces. In this scenario, the declining state has two options: attack immediately, accepting the burdens of the offensive; or wait, allowing the adversary to build up a larger force inventory, in the hopes that this will be outweighed by the advantages of the defence. The model does not provide a clear answer to this question until after all parameters have been specified and complicated mathematical comparisons are made. As Clausewitz noted, the choice between fighting a defensive battle in the future and an offensive battle in the present is rarely clear-cut and it is impossible to deduce from an eroding force ratio the need to attack immediately (1982: 115).

VI. Conclusion

6.1 Testable propositions derived from the theory

It is perhaps ironic that a model built with a view towards predictive accuracy was not submitted to any rigorous empirical tests. This was a factor of both space requirements and the nature of the model's parameters. In order to successfully test the model, several parameters must be "pinned down" by exploratory empirical work. These include the depreciation rate of force inventories, the (rough) discount rate used by most states, production constraints (η), etc. Economists have been engaged in similar problems for decades and are only now reaching consensus on these background empirical issues.

Following in the tradition of Downs (1957) this section presents a list of testable properties which could be used to evaluate the theory's predictions and generate numerical values for model parameters.

- Nations engaged in purely defensive arms walks will increase military spending proportional to their combined rates of economic growth, adjusted by the margin of defensive superiority (Weak form).
- Nations engaged in a defensive arms walk will increase their military spending according to the formula $(g_A + g_B) / (r\text{-}1)$ (Strong form).
- Unilateral increases in force by one side will be met with reactive force increases that are smaller in size from the adversary.
- Significant demobilization will follow the elimination of one state in a dyadic rivalry.
- States which initiate wars will possess large margins of superiority over their target.
- States balance both against existing enemy force levels and enemy mobilization capacity (Weak from).
- States maintain peace time forces proportional to the economy of the adversary (η), adjusted by the margin of defensive superiority (r-1). Their force levels are not influenced by the size of their own economies, the

level of hostility between the two states or the actual level of enemy forces. (Strong form).

- Military spending is kept to the minimal level consistent with security during peace time.
- Defence-promoting (offence-promoting) technological shifts will reduce (increase) standing military forces for all states.
- States maintain rough military parity with one another, even if their economies differ in size.
- Negotiated resources transfers to avoid war are rare.
- Governments with longer time horizons are more prone to offensive arms racing.
- Arms racing is rare in periods of great defensive superiority.
- Areas of the world with very different growth rates will give rise to large numbers of arms races and wars.
- War initiation following an arms race should almost always end in victory for the attacker.
- Unilateral disarmament is rare.
- States are sensitive to even small changes in force levels near equilibrium.

6.2 Implications for security studies and political science research

This model aimed to contribute not just in the specific conclusions at which it arrived, but also by the manner in which they were derived. As the long discussion of analytical priors and the numerous assumptions make clear, even relatively simple conclusions require in-depth analysis if those conclusions are to be logically sound. Many political scientists do not follow the practice of making their assumptions explicit, or fail to make the necessary assumptions to prove their assertions (i.e. Waltz (1979) makes claims about the stability of bipolar and multipolar systems before he has introduced the analytical machinery necessary to sustain those claims).

Another important aspect of the assumptions made in the course of this paper is their concentration on fundamentally physical aspects of international politics. The realist school has long been characterized by a focus on physical realities over ideational factors (Joseph 2005), but this focus is often highly abstract – sometimes consisting of little more than the use of a "power" variable. This paper has focused on a more specific, concrete physical reality. Military power was rendered precisely, it was embedded it within the physical realities of combat (as captured y the offence-defence balance), and the model even included a variable reflecting depreciation of force inventories. These decisions played a key role in deriving the conclusions in the previous section, and even small changes (such as allowing r to fall below 1) would dramatically change the predictions of the model. This suggests that realists should focus not just on physical reality, but on *specific* physical realities. Political scientists studying international relations must, in effect, roll up their metaphorical sleeves and study in detail the variables which are of concern to decision-makers. After all, the signing of the partial nuclear test-ban treaty in 1963 was as much due to technical developments (i.e. non-intrusive testing methods) as political ones (Gaddis 1998: 164).

Lastly, the predictions of the model (once fully parameterized) are extremely precise. By testing the evolution of "mature" arms races such as the US Soviet case, the Anglo-Germany naval rivalry, or conventional races between India and Pakistan, it is possible to come to a swift conclusion about the validity of the model. If the model's predictions hold, this is a strong sign that the model's logic is correct, since precise predictions are more likely to be falsified than vague predictions. At this point, second-order predictions of the model could be tested on the same data. If the predictions fail, the manner in which they fail may provide a clue towards which assumptions are inappropriate for the realm of international security competition. For example, if states maintain force inventories that are far larger than those predicted by the DCF, this may suggest that states are hedging against multiple periods of military production, which in turn implies that the perfect information assumption is faulty. This would direct our attention towards uncertainty-based models. A different set of failures would suggest completely different remedies. This compares favourably with current political science practice, which typically tests theories in their entirety, and is thus incapable of diagnosing the source of predictive failure.

These are three broad areas in which the model's epistemology can contribute to the study of international security. The relevance of the model's empirical predictions depend, of course, on its subsequent validation. To assert otherwise would betray the analytical priors which were set out in great detail in chapter 1. Relatively simple models, founded on clear assumptions, and which address answerable questions, are a promising foundation for progress in international relations. It is hoped that the findings of this paper contribute to greater consensus on methodology and epistemology, if not on substantive theory. The relevance of the subject is also pressing. Regardless of whether one believes that great power politics will continue to generate conflict (Mearsheimer 2001) or in the obsolescence of major war (Mueller 1989) it is imperative to understand the sources of conflict in order to manage them or prevent their re-emergence. This model is, if not a step in the right direction, at least a move whose wisdom can be easily assessed.

Appendix: Variable List

Notation

$_A$	subscript A denotes state A
$_B$	subscript B denotes state B
$_t$	subscript t denotes an arbitrary time period. Superscript t is "to the exponent of t"
*	superscript asterix represents the equilibrium value of a variable
Σ	the summation operator

Variables and Parameters

S	a state's resource base
s	any fraction of a state's resource base
s_f	the quantity of a state's resource fed in to the force function
δ	the discount rate
v(x)	the value function
f(x)	the force function
r	the minimum ratio of attacking to defending forces at which the attacker will be defeated
p	the fraction of a state's resource base that is transferred to the victor after war
η	the maximum increase in force that a state can produce in a single period
c	the probability that a state will win an offensive war at a given correlation of forces
C(x)	the contest success function that determines c

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