REVIEW COPY

ANATOMY OF A COMBAT MODEL

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Prepared as part of a long-term contribution to the field.

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1. INTRODUCTION

> "The most crucial problem affecting the analytical or simulation modeling of combat at virtually any level of intensity is identified as the lack of a body of knowledge, or a theory, that defines the relationship between combat modeling and the conduct of war in the real world." Lawrence J. Low, "Theater-Level Gaming and Analysis Workshop for Force Planning," September 1977.

This paper addresses the still-current question "what constitutes an all-inclusive set of specifications for a combat model?" It is based on an extensive (and extended) effort to develop a theory of combat that started as an organized endeavor in 1979. As such, the paper is an application of theoretical developments that have evolved to date in that undertaking and outlines an idealized, universal modeling structure for military operations across the entire spectrum of warfighting. Its applicability is considered to be independent of:

- Warfare domain (land, sea, air, space) and associated military force structures
- Level and intensity of conflict and size of engaged forces
- Modeling techniques used (e.g., closed-form mathematics, computer simulation, war gang)
- Degree of combat resolution or granularity in the model
- Application of the model (whether to problems of training, education, force planning, battle management, or product research and development)

An unfortunate tradition has developed over some four decades of military analysis leading to an entrenchment of the *ad-hoc* building of warfare models. With precious little of scientific method to go by and relying primarily on the writings of historians and military theorists (Sun Tzu, von Clausewitz, Mahan, Jomini, etc.) as well as current collective military experience analysts have boldly warped mathematics and computers to the task of modeling all forms of combat and war. Most often, models were created to address specific defense issues; each time the modeler started anew to build a model that emulated the systems and processes believed to be germane to the problem at hand, using techniques described later in the paper (Section 5.0). Should the model later be questioned in an adversarial environment (as has often been the case), the developer, who had proceeded in largely heuristic fashion, could only defend his/her model with great passion, and appeals to reason because no formalism for the model had ever been established. It has only been within the last decade or so that a recognizable effort has coalesced in the military modeling community that critically attempts to assess the pros and cons of the many models and modeling techniques that have been put to use and where the most serious omissions and shortcomings in our models lie. This, in effect, has been an attempt to establish a professional group testimonial as to what may be good and what is not so good in modeling while efforts at combat model validation, sorely needed, are complex, costly and proceed ever so slowly. Thus, we still lack a general formalism for combat.

The present work constitutes a straw man for such a formalism that is based on historical evidence, continuing military experience, and fundamental ORSA[1] concepts. As stated earlier, it springs from attempts to develop a combat theory. In such an effort, one continually looks for patterns of consistency and order in what otherwise appears to be a chaotic phenomenon. Having found such patterns, one then probes for the boundaries of their widest applicability under varying conditions and situations. It is around such clusters of more general truths that the body of a theory takes its form, only to be subjected to further prodding and testing as new evidence and new data surface. When necessary, subsequent modifications are made to the "theory" hypotheses that were developed in the manner described.

The modeling structure described in what follows serves to define the general specifications for combat modeling. This structure is idealized in the sense that a significant number of related factors fall well beyond present modeling capabilities but, from a preponderance of historical evidence, are nonetheless critical to a faithful representation of combat phenomena. (Factors in need of further investigation are identified.) Furthermore, the material presented is descriptive rather than prescriptive or predictive. In short, we attempt to *describe* the interactions and course of combat before efforts are made to model these computationally or algorithmically (generally accepted as a logical first step in the model-building process). Thus, we are addressing the structure or framework of a model, rather than an actual working model. In some sense, we are looking at a model of a model.

The presentation in the main body of this paper avoids much of the definitional material and elemental discussion associated with theory development, which tend to

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1 Operations Research/Systems Analysis

interrupt the primary thrust of our exposition. Instead, some of this more fundamental information is presented in appendices to provide additional clarification and some further measure of analytical depth.

Next, some of the key issues involved with combat models are discussed within the context and as an application of the modeling structure presented in the paper. This is mainly done to round out a picture of the practical limitations that exist on such modeling today. We finally conclude with some suggestions on how to proceed with a program designed to improve our understanding of combat processes and our abilities to model them.

2. COMBAT MODELING - WHY BOTHER?

The fundamental purpose for attempting to model a complex phenomenon is usually to produce an instrument for the *measurement* of processes that can be used under laboratory-like conditions of experimental control. The ability to measure requires the use of some form of mathematical abstraction (i.e., a model) of the combat phenomenon, to whatever extent is sound and possible. If we attempt to model anything as complex as combat, then the instrument we develop should be scientifically faithful to, even though remote from, the conditions that prevail in the battle areas and the combat experiments of the real world. By modeling combat we hope to gain better insights into the countless interactions that occur among men, equipment, and their environments during battle in order to understand more fully which variables are driving the combat process under what sets of circumstances. Furthermore, we will seek to identify the relative effects of these variables on combat and how conditions for one side over another might be altered in a desired way by manipulation of such variables (the prescriptive use of models). Ultimately we would like to predict with reasonable confidence, and in some measurable way, the outcomes of combat events, of battles, and of wars (the predictive use of models).

The knowledge that can be provided by a sound model is of importance. Valid models constructed in various ways can have many applications such as:

- Training of personnel in the conduct of warfare
- Education of personnel in military science and theory (service academies and war colleges)
- Development and evaluation of operational concepts, doctrine, and plans
- Development of military force structures and determination of force levels
- Assessment of logistics and force support requirements
- Development and evaluation of military systems and equipment
- Battle management in real time and as adjunct to decision aids.

In large measure, models and simulations help alleviate the need to rely solely on military experience and judgment for answers, or on more costly, unwieldy alternatives such as combat experiments and exercises that are difficult to control. Fundamental to this of course, is the use of valid models. Despite some recent efforts that show promise, we still have a long way to go in establishing combat model validity to within acceptable standards of certainty in a scientific sense. A major impetus behind the use of models lies in the experimental *control* that they afford, but much remains to be done to establish real confidence and credibility in the process of modeling combat. More appears on these modeling issues in later sections of this paper.

3. AN OVERVIEW OF COMBAT AND WAR

At the outset, a brief discussion of some fundamental concepts advanced by the Military Conflict Institute (DuBois *et al.*, unpublished manuscript)[2][2] is in order because these form the foundation of our formalism. First and foremost is the notion of military combat as a uniquely human activity within the realm of all animal behavior wherein extensive deadly force (or the threat thereof) is brought to bear by antagonists of the same species to achieve control (physical or cognitive) over an opponent. Military combat is generally characterized by the use of weapons or arms and supporting devices to augment innate yet limited human capabilities in basic musculoskeletal strength and in areas of sensing, memory, and data processing. The duration of actual combat is the period of time encompassing the steady, consistent application of deadly force by either opponent (or by both). A combat event is a broader overarching concept of longer duration within which actual combat, when it occurs, is imbedded. Military operations associated with an event are all tied to a specific set of initial conditions that include definitive missions to be carried out by both sides. The duration of a combat event is measured from the decision time of intent by either opponent to use deadly force against the other (whether or not such use ever materializes) to the time of event termination established by any of the following:

- Annihilation of either side (destruction)
- Capitulation by either side (surrender)
- Unopposed withdrawal of either side (retreat, rout)
- Mutual decision by both sides to disengage (stalemate, de-escalation).

It follows that all forms of warfare (tactical nuclear down through conventional) and levels of warfare (global/theater down to one-on-one duels) can be thought of as episodic collections of distinctive combat events, varying in scope and intensity, that occur both serially and in parallel. In modeling a war, these combat events are bound together by their connections to sets of higher-echelon military goals and objectives for both sides that determine the tactical mission for the engaged combat forces in the scenario.

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2 References are listed at the end of the paper.

In addition, the overall conduct of episodic combat in warfare is influenced by a number of contextual factors or variables that are exogenous to the war fighting per se, are largely behavioral or sociological in nature, and are important to, but vary with, the particular conflict situation under study. These factors are said to be *situation-dependent.* Once the fighting starts, these factors, in turn, can be modified or altered by outcome developments from on-going sequences of combat events.

Last, but no less important, is the fact that all of the activity described occurs within, and is directly influenced by the geophysical environment of the combat locale (the arena) with its associated geography and terrain, meteorology, and climatology.

Figure 1 illustrates in simple, summary fashion some of the fundamental relationships discussed. In general, we are concerned with those "External Contextual Factors" for both sides that affect the missions for the combatant forces and their morale, leadership, and overall combat performance. The "Support" arrows in the figure signify important considerations of supply, engineering, and medical support to the combatants and the "Feedback" shown reflects the cumulative effects of combat-event outcome in altering or modifying the forces involved, the combat arena, and the external factors. Time, the variable, is not a consideration in Figure 1 in that the relationships show (although not necessarily their degree or magnitude) are time-independent in nature.

Much of the remainder of this paper is devoted to amplification of the above material.

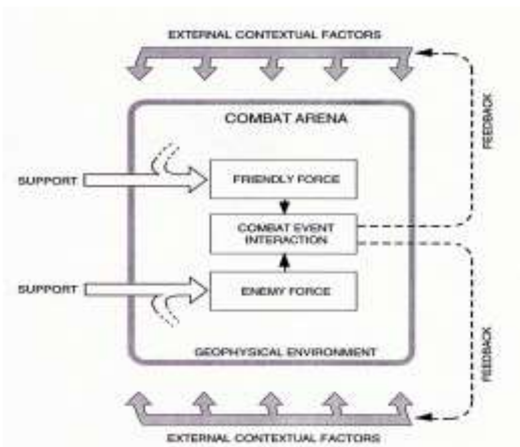


Figure 1. Some basic relationships in warfare.

4. COMBAT AND WAR ACTIVITY IN THE TIME DOMAIN

A useful analogy in viewing combat events is to think of the process as the horizontal stacking of a series of "snapshots" along a time line. Each snapshot is an instantaneous picture of all the on-going military activity at some single point in time during the course of a combat event and the pictures are spaced in time from one another by an increment, A_t. The first picture in the stack corresponds to combat event initiation and the last to event termination (Section 3). Obviously, the size of the stack will depend on the duration of the combat event and, in the limit, if we allow A_t-4 0, we have a continuum of activities and their interactions from event start to finish.

4.1 A SNAPSHOT (FIXED-TIME CROSS SECTION) OF COMBAT ACTIVITY

It is highly fortuitous that a level of abstraction in the modeling of combat can be found that allows us to construct a universal picture of the fixed-time (instantaneous) activity interactions that occur in all time frames of combat. This picture depicts the substance and nature of the interactions, recognizing that their degree or intensity can show wide individual variation as we move among time frames (even to the point of being temporarily, but altogether absent). Such a picture is shown in Figure 2, a much expanded version of Figure 1.

Figure 2 is a fixed-time abstraction of the factors that a combat model should address. In describing the figure, the material presented is wholly expository in nature neglecting, for the present, deficiencies that are to be found in much of current modeling practice. A discussion of long-standing problem areas that plague the model-builder is presented in Section 8.0.

At a glance, it is clear that Figure 2 is symmetrical about a horizontal centerline and reflects the existence of friendly and enemy forces with their respective commanders and staffs. This explicitly establishes the model as one involving a *two-sided* decision and execution process. Both friendly and enemy commanders are assumed to fit into an organizational hierarchy that is reflected in the figure by the call-out of superior, lateral, and subordinate commands. Both commanders operate in accordance with assigned missions that are, in essence twin-engine drivers for the entire war-fighting process. To carry out their respective missions, the commanders control both combat and logistic forces which, in the most basic terms, are composed of manpower and material. The specific composition and configuration of these forces will, of course, vary greatly with the combat domain (land, sea, air or "combined arms") imposed by the conflict scenario.

The forces interact within the combat arena under influence of the geophysical environment, the interactions occurring in pulses of activity defined as combat events. The events give rise to a flow of combat results over time that are grounded in absolute, "model"

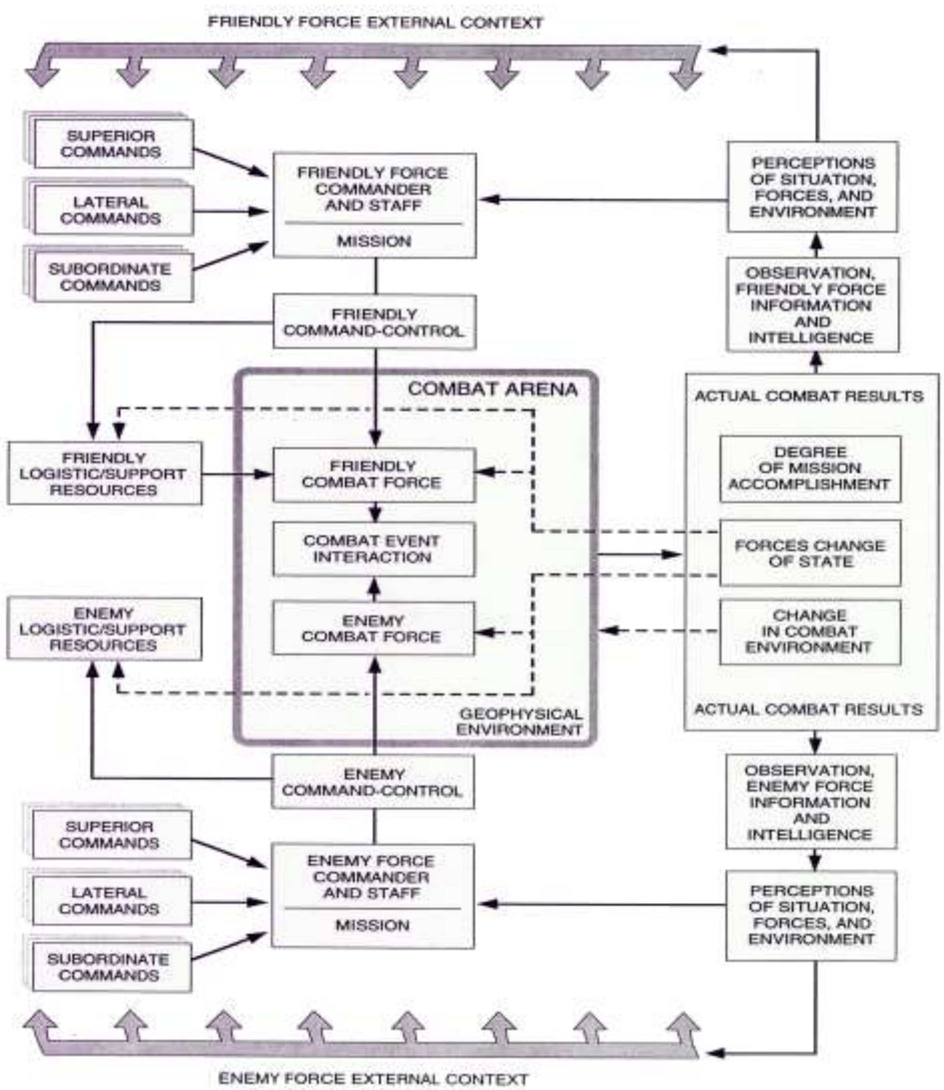


Figure 2. Fixed-time cross section of combat.

truth (commonly referred to as "ground truth"[3]). These results reflect the progress being made toward mission accomplishment by both sides, changes in force states for both sides, and changes to the environment produced by combat event activity. (Force state and state change are discussed in greater detail in Appendix A.)

Assimilation of actual combat results into some form of friendly and enemy cognition occurs through observation and absorption of these results by intelligence/information gathering nets and systems possessed by both sides. The information thus filtered, however, may be untimely, incomplete, or in error relative to absolute model truth. Yet it is upon such information, after the processing and integration of data, that friendly and enemy perceptions of their status and progress in battle are based. These perceptions, in turn-coupled with external context factors that can be undergoing significant change during combat-influence friendly and enemy command decision-making for the further control of forces in the prosecution of war. All of the above steps are shown in Figure 2 (with feedback designated by dotted arrows). Suitable networks of communications, though not shown, are implied for both sides.

4.2 STACKING THE SNAPSHOTS

Figure 2 concerned the instantaneous cross section of combat activity in the time domain. It clearly shows how a cyclic pattern evolves of two loops (friendly and enemy) of information-decision-action that interact with one another in the combat arena. Any combat model can be viewed as a stack of Figure 2 facsimiles established on a time line that extends from time of combat event initiation to event termination. Before actually taking such a step, however, we simplify Figure 2 to Figure 3. Then, in Figures 4(a) and 4(b) we reduce the fixed-time functions for both sides to five intersecting circles. These circles represent friendly and enemy C^3h Logistics/Support, and Active Fighting, all closely interrelated. The main interaction between opposing forces then occurs through the active-fighting circles that largely overlap one another in the combat arena.

The next step is the construction of a combat model picture in the time domain, shown as Figure 5. Here, the external context variables for each side influence combat from beginning to end, mainly through continuing constraints imposed on and impetus provided to the combat commanders and their forces. Initial conditions provide a starting boundary for each side (t=0). At each point of time (as for example at t_1, t2, or t3) the

[3] This truth descriptor undoubtedly springs from the modeling of land warfare but can easily be extended in concept to the other elemental warfare domains of sea and air.

same symmetrical patterns of forces and activity relationships hold for the two protagonists. The intersecting combat function circles representing C^3I, Support, and Active Fighting, as derived in Fig. 4, extend over time in the form of a tube whose cross section has two pairs of projecting lobes. Although shown as intersecting cylinders of uniform diameter, the tube should more properly be portrayed with cylinders of varying diameter, expanding and contracting over time to reflect the changing intensity of $C^3 1$, Support, and Active Fighting as the combat proceeds. The important aspect of this representation is the emphasis it places on continuing interactions among the most basic functions on both sides of the fighting.

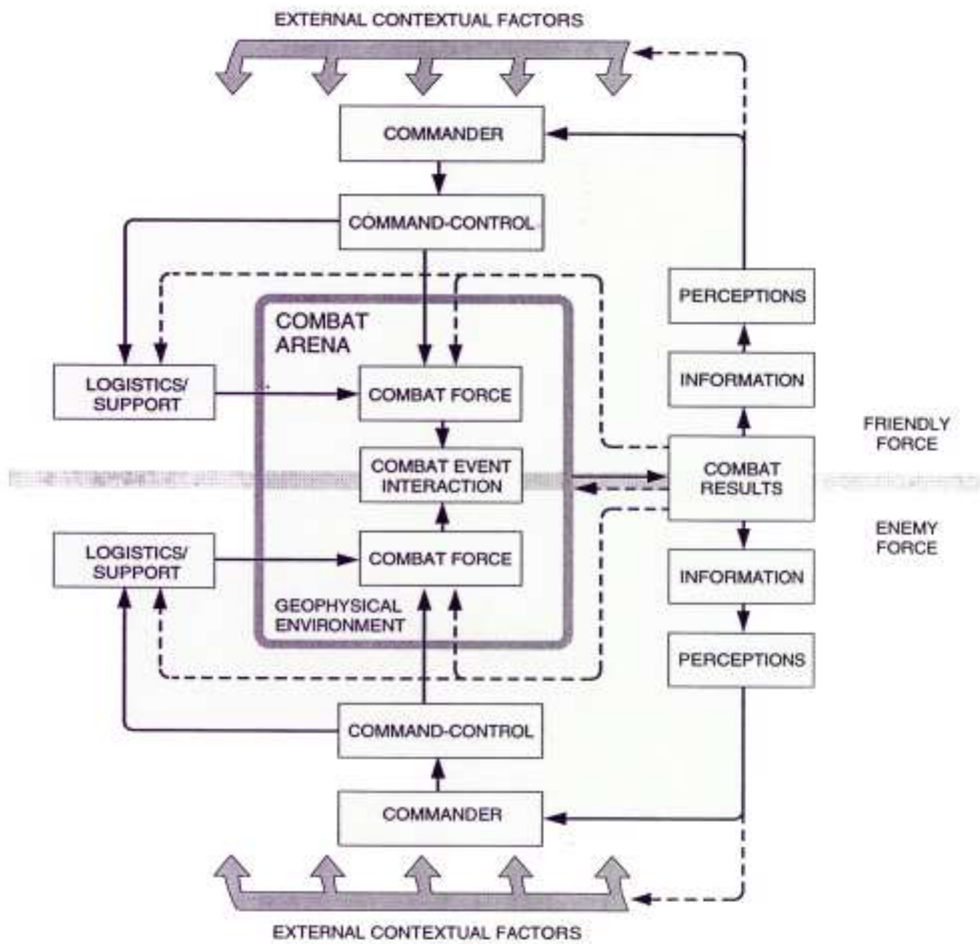
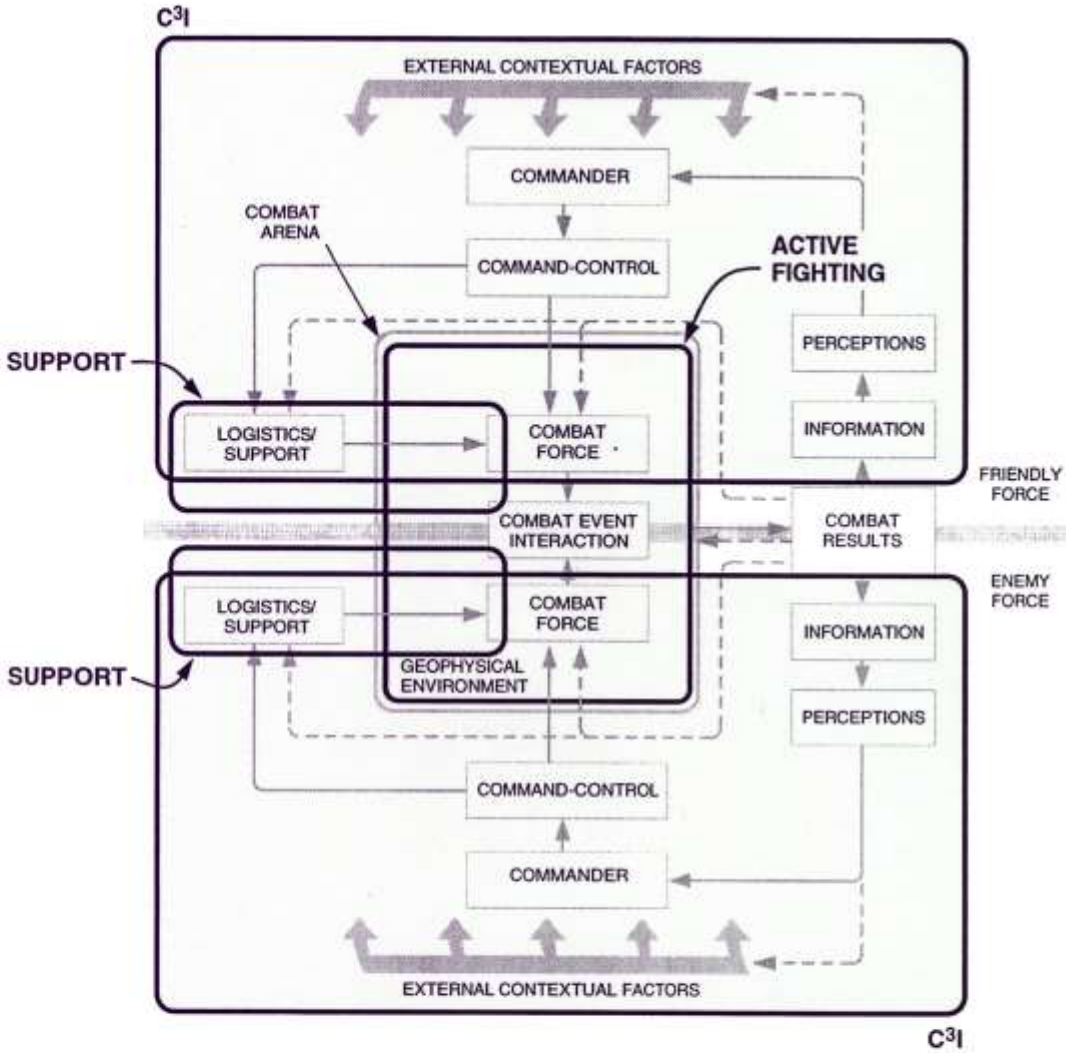
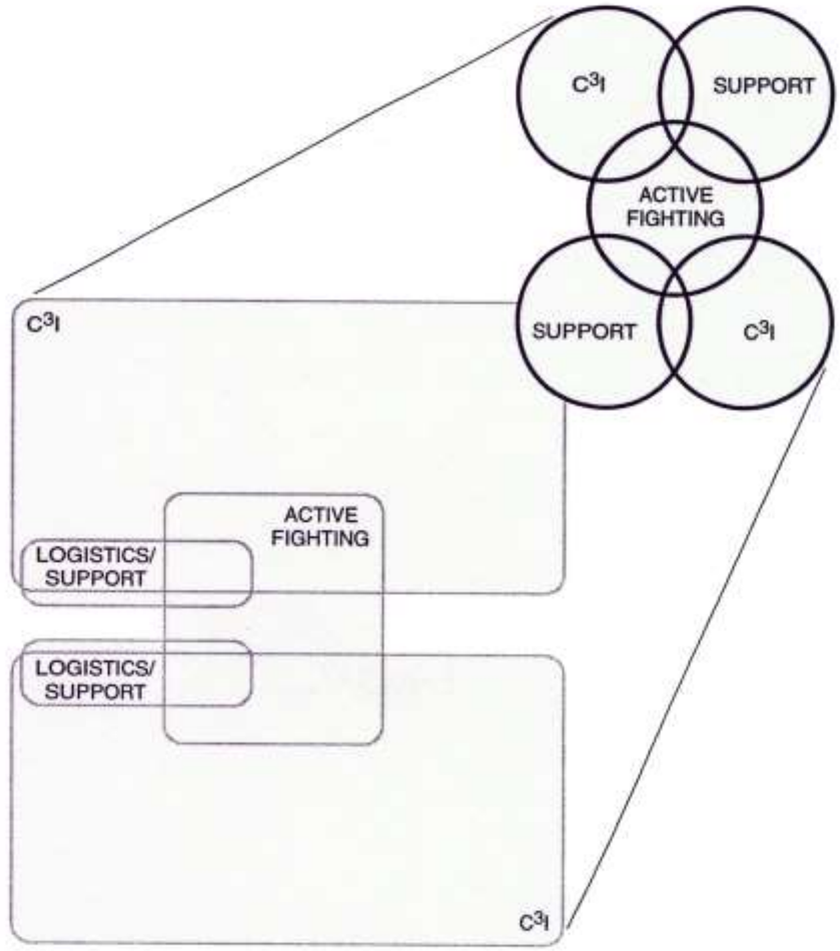


Figure 3. Simplified fixed-time cross section of combat.



(a) STEP 1

Figure 4. Aggregated fixed-time cross section of combat.



(b) STEP 2

Figure 4. Aggregated fixed-time cross section of combat (concluded)

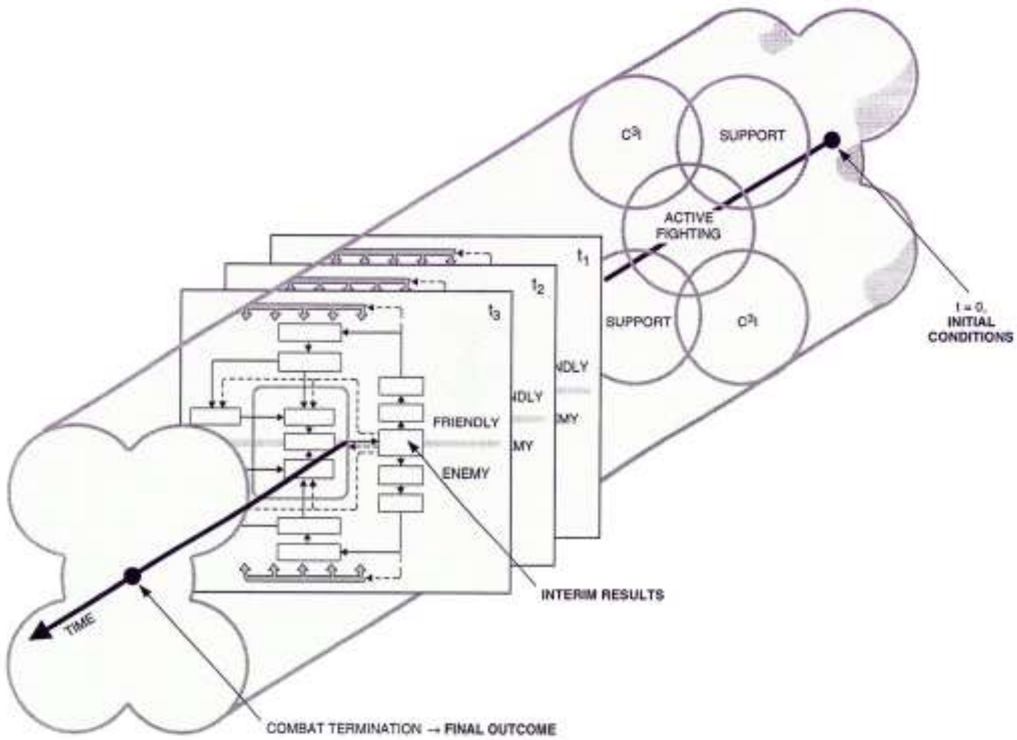


Figure 5. Combat in the time continuum

The combat results at each time point (interim results) act to alter the combat situation, leading to a new situation at the next time point, and so on to the termination of combat. Combat termination generally occurs when the interim results are compatible with the missions and objectives of one side or the other which, like external context, can change during the game. Those final interim results are designated as the combat outcome. More specifically, termination will find force states and postures in one or more of the four conditions outlined in Section 3.

5. MODEL BUILDING METHODOLOGY

The form taken by a combat model should be one that best enables it to serve a useful purpose in military analysis. One main purpose of modeling is to create an instrument for measuring the dynamic behavior of complex interacting systems. It is the mensuration goal that clearly calls for phenomenon quantification to whatever extent is possible and hence the need for the use of mathematical modeling techniques. A quick review of these techniques as they pertain to combat is in order.

Most traditional of the techniques for process modeling is the closed-form mathematical equation that expresses the relationship between dependent and independent process variables. A classical example of this is given by Lanchester's equations: simultaneous differential equations of attrition rates for two engaged forces as functions of both individual combatant kill rates against an enemy and the force levels for both sides. The solution to these equations is a closed-form expression of how two forces numerically decay with time as a result of attrition caused by the opposite side (developed for the two separate cases of directed fire and area fire). `In the Lanchester example, attrition is the primary combat process being modeled explicitly, though within the process, implicit assumptions are made relative to target acquisition and firing doctrines for both sides.

It is appropriate at this point to portray the totality of combat (as thus far developed in Section 4) to be an exceedingly intricate process, composed of component subprocesses that produce corresponding generic components of the interim results shown in Figure 5. These component subprocesses are designated as primary combat processes[4] (see also Appendix B for further discussion and definition). The primary processes are interdependent to varying degrees and, as such, cannot be expressed in singular mathematical form but require a system of complex, simultaneous equations (which, to begin with, are virtually impossible to write) for a solution. When, as is most

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[4] Combat processes are attrition/destruction, suppression, neutralization, demoralization, maneuver, disruption, deception, command-control (C^2), motivation, information acquisition, communication, movement, protection, and sustainment. Processes differ from functions (Section 4.2) in that processes deal with the action and counteraction activities of two opponents whereas functions concern only one-sided moves or actions by either opponent, without regard for enemy reaction. There are several instances of processes and functions having identical names although they differ in concept.

often the case in any combat situation, more than two processes are involved in the sequence of activities, we must turn to the digital computer and the simulation techniques it affords in order to solve our modeling problems in a practical manner.

In traditional simulation work, we develop computer code that dynamically interweaves the workings of all the combatants and their weapon and support systems, on an operational step-by-step, event-by-event basis, using either time-step or event-store programming techniques. By diligently simulating all activity in this manner, we automatically account for the interaction of the combat processes as they ultimately contribute to combat results and, finally, to combat outcome.

The concept of primary combat processes affords us a particular way of roughly subdividing the combat activity pie-and the results this activity produces-into segments that have military operational significance and can be compared with the missions of both sides to gauge combat progress and to help establish combat termination. However, we recognize that some of the processes, although definable in a military sense and traceable in historic situations, remain most difficult (or impossible) to express explicitly in modeling terms. This is particularly true of processes that are mostly cognitive rather than physical (i.e., command-control, deception demoralization).

It is to accommodate the cognitive aspects of primary processes and other behavioral factors in combat that we resort to the introduction of "man-in-the-loop"; that is, human interaction with computer simulation. In this composite form of model/game, humans make "combat" decisions and the computer produces the consequences with advanced forms of graphic displays available to effect an interface between the two. At the same time, continuing efforts are being made to develop suitable algorithms for the modeling of cognitive activity in combat, such as C^2, largely through the use of AI techniques.

In building a combat model, it is necessary to account for all of the fixed-time interactions of Fig. 2 and to effect their integration over time in accordance with Fig. 5, using any or all of the modeling techniques briefly outlined above. All work would proceed from some specification of scenario, which establishes the context, the scale and scope, and the initial and boundary conditions for the entire exercise. Actual model construction is the "moment of truth" in verifying one's true comprehension of how a particular complex system functions. For combat, the manner in which men and equipment perform under conditions of enemy counter activity in some specified environment must be well defined and understood before it can be represented in model format. In addition to the process modeling effort called for, there is a significant task involving assembly of a database that includes all initial condition, environmental, and systems variables for the conflict as well as other constraints that may be operative. These are commonly referred to as "inputs" to the model and they must be collected at considerable effort and verified with care (if not, "garbage in, garbage out"). In Section 6, we discuss the influence of external context and the input data requirements for a combat model.

6. COMBAT CONTEXT AND MODEL INPUTS

Combat does not occur as a closed or isolated system within the natural and sociological environments that foster its existence. Its conduct, which we attempt to model, is strongly shaped by external factors of context that influence the combat throughout its course; by certain initial conditions, states of forces and the environment, orders of battle, equipment, and performance variables; and by the intended outcome and conditions subsequent to the combat sought by each side.

The initial conditions, orders of battle, and equipment performance variables (referred to above as inputs) cover the missions and all information that defines and describes the states of human and materiel resources on both sides of the conflict at its outset, along with the initial deployment coordinates of these resources. Also included are values for the variables that relate to resource properties, characteristics, and performance. There can be considerable trade-off of certain types of input information against process modeling tasks internal to a combat simulation, making the determination of model input very much a part of model construction.

The external context factors include the combat scenario (background, circumstances and scope of combat), the geophysical environment with its properties and characteristics and other contextual variables (mainly historical, cultural, or sociological). External context factors are likely to assume increasing importance in U.S. contingency gaming as greater extremes of variation are encountered in the geographies, historical backgrounds, and cultures of possible trouble areas around the globe. In contrast to the potential "western-style" adversary that prevailed in 45 years of Cold War planning, the smaller conflicts that can now erupt almost anywhere are likely to be as profoundly affected by the constraints of external context as by any actual fighting that might occur. However, even granting the importance of combat context in modeling (too often neglected), there are serious difficulties with its application to the modeling process that are fundamental to all variables and combat processes that are behavioral or cognitive in nature. These stem from an existing reasonable capability to model and measure physical activity and performance in combat that is far from being matched by any corresponding ability with cognitive matters. In fact, all of the outcomes in combat modeling to which measures of effectiveness (discussed later) are related are based on the results of physical activity (aircraft destroyed, ground gained or lost, etc.) that should incorporate and reflect the significant behavioral characteristics of the opponents. Since these continue to defy modeling efforts and are most difficult to measure in a meaningful way, the emergence of the art-form aspects of combat modeling comes with attempts to establish in some rational manner the impact of "soft" variables such as national will, morale, or readiness on combat performance and physical combat activity. Perhaps the careful study of historical evidence or the conduct of controlled behavioral experiments can lead to a better understanding of this coupling between cognitive and physical matters in combat. This extremely complex yet crucial subject is perhaps the main deficiency in model-based combat analysis and should be a principal focus of future research.

Despite the difficulties, it is nonetheless useful in working toward modeling goals to address in greater detail the variables that constitute input and establish context in models and simulations. This is done below.

6.1 CONTEXTUAL FACTORS

Many of the context variables lack an exactness of definition and therefore, for the present, defy numerical evaluation. Yet they are like the lining of a pocket placed in some event stream into which the combat being modeled can fit in seamless fashion. This is the major modeling connection between combat and its surrounding circumstances that experience tells us is most important in evaluating reality. About the best that can currently be hoped for in allowing such context variables to influence the working of a model is to somehow specify their effects on other appropriate input variables that couple directly into model process subroutines (as for example, the effect of "national will" on "Lanchester attrition coefficients"). This can be an impressively tall order that, for the present, is rationally best handled by military experience or historical analyses of what are believed to be similar or related conflict situations.

The box identifies a number of contextual factors. We could as easily have gathered descriptors and variables of the geophysical environment into a separate, independent grouping but instead are treating them as part of combat context.

COMBAT CONTEXT

Combat context (defined for both sides) includes the following:

- Geopolitical and military circumstances of the broader conflict (when applicable) in which combat occurs. Includes, but is not restricted to: alliances and coalitions; geographical areas affected (combat zones, logistic lines of communication); pertinent political, economic, scientific, industrial, and cultural trends; national war strategy; purpose and value of combat outcome to the broader conflict.
- National will and support of the war in home countries and (as appropriate) in the host country. Includes, but is not restricted to: degree of governmental authority and control; military traditions and discipline; circumstances leading to the combat event, including prior combat; directives and constraints imposed by higher commands; combat mission; intentions of higher command subsequent to the combat action.
- Geophysical environment is associated with the combat area and logistic lines of communication as follows:
  - Earth science profile for extended combat arena (selectively defined, as appropriate, to include geological, oceanographic, aerographic characteristics)
  - Physical terrain
  - Vegetation
  - Climate
  - Weather
  - **Man-made changes to the natural environment**

6.2 MODEL INPUTS

In this section we identify the inputs to combat models down to some general yet reasonably detailed level that outlines the categories of information ideally required for an all-inclusive, realistic model of combat. The inputs are the set of factors (variables) directly related to the combat and their values at the outset of the combat event. Many of these variables appear and operate directly within the model subroutines; others, as we discussed above, are not a fundamental part of the process subroutines but have effects (often not easily measured) on the variables that are explicitly involved. After the fighting starts, the model subroutines interact in a way that may change the values (quantitatively or qualitatively) of many of these input variables over the duration period of the combat event.

The format, volume, and detail of the input to a specific model will be closely tied to certain model characteristics in the model's application to some problem. Most notably these are (1) the scope of the conflict modeled; (2) model granularity; (3) warfare domains involved in the combat, and (4) the extent to which input data serve as a substitute for explicit modeling in design of the combat model. These factors, unquestionably the most influential in determining the size and content of the input database, are discussed further subsequently.

6.2.1 Initial Conditions/Orders of Battle

All information presented in the box below applies to both sides of the conflict.

INITIAL CONDITIONS/ORDERS OF BATTLE

Organization and Structure of Forces

- Command structure, which includes command/staff operating principles and plans; command, control lines and nodes; communication links; intelligence gathering (combat, strategic) and dissemination networks; friendly force information dissemination.
- Combat and logistic force structure and deployment, which includes combat force unit (land, sea, air) descriptions, deployments, and chains of command; logistic force unit descriptions, deployments, and chains of command; conventional/special support units and deployments.

Operations Concepts and Doctrine

- Strategic guidelines for combat (related to Combat Context in 6.1)
- Customary operational procedures, including, but not restricted to: tasking sequences; methods of system employment; methods of employing logistic forces
- Rules of engagement (related to Combat Context in 6.1)
- Strength of adherence to tactical and doctrinal concepts
- State of command/staff knowledge (concerning own forces, enemy forces, environment)

Manpower

- Numerical strength by units (combat and support)
- Manpower characteristics, including training and readiness, morale and discipline, leadership, will, and motivation to fight

6.2.2 Materiel Inputs

Combat materiel embraces all of the physical equipment, spares and supply elements that, along with manpower resources, constitute the array of man-machine systems used in warfare (see the box below). These systems vary greatly in size, complexity and degree of automation. How well they ultimately perform in battle depends on (1) the doctrine governing their manner of employment, (2) the skill of the human operators, (3) the performance capability engineered into the equipment, (4) system interactions with the geophysical environment, and (5) enemy counter activities against the system. "Materiel input" to a model can vary greatly as to volume and detail.

In our listing of materiel, we refrain from lengthy, elaborate taxonomies of equipment that cascade out laterally and downward as we go from complete systems to major elements, assemblies, subassemblies, components, and so forth. For summary purposes, we note that for any system falling into one of the classes shown below, our input interests focus on (1) the manner of equipment integration into the military hierarchy and the means of command control, (2) the number of equipments initially on hand and their deployment, (3) a description of the system, its operating mode(s), and physical characteristics pertinent to combat operations, and (4) engineering and test performance characteristics over the design operating spectrum.

Even a highly aggregated, abbreviated, breakdown of materiel provides some appreciation for the large volumes of technical input data needed to model conflicts of any scope or size, particularly when they are to be modeled in fine granularity (or high resolution).

MATERIEL INPUTS

Seven general classes of systems are of interest:

- **Combat vehicles/weapons platforms**

  Consists of all combat vehicles operating on land, air, sea/undersea, or in an amphibious mode, as appropriate to the scenario. Includes tracked and wheeled land vehicles, fixed- and rotary-wing aircraft, aerostats, surface-effect vehicles, and so on. These, in turn, consist of many specific mobile carrier systems in categories of tanks, armored personnel carriers, aircraft, helicopters, surface ships, submarines, landing craft, and the like.

- **Weapon systems**

  Consists of all forms of weaponry, whether offensive, defensive, or dual-purpose, and whether in use on the surface (land, sea), in air, or undersea for use against air, surface, or undersurface targets. Includes systems employing guided or unguided munitions, using active or passive sensors (including electromagnetic, magnetic anomaly, infrared, acoustic, electro-optical, chemical/aerosol detectors), equipped with conventional warheads (e.g., high explosive, armor piercing) or unconventional warheads (nuclear, chemical, biological). Also included are all types of small arms, automatic weapons, and the explosive, incendiary, and demolition devices employed in sabotage/terrorist activities.

- **Command control systems**

  Includes command data links, displays, data-processing systems, decision aids and security systems.

- **Communication systems**

  Includes significant land-line voice links, satellite links, radio communications (multifrequency), closed-circuit TV.

- **Intelligence systems**

  Includes all terrestrial, airborne, and satellite-based sensing for detecting the presence and activities of hostile units/forces, for mapping and for the detection of environmental changes.

- **Deception and countermeasures systems**

  Includes (but is not limited to) the use of camouflage, decoys of many types, and countermeasures (electronic, acoustic, thermal emission, and so on).

- **Logistics and support systems**

  Includes all airlift, sealift, and overland transport systems and vehicles, as well as in-flight refueling and naval underway replenishment systems. Requires definition/identification of significant rail and road networks and other major transport routes, of supply centers and depots, of resources for engineering construction and repair, and of medical services and facilities.

7. SOME COMFORTING WINDFALLS FROM COMBAT MODELING

The following sections discuss certain patterns that have emerged from extensive conceptual work in combat modeling. They help significantly in tidying up the clutter that seems to prevail at the tactical action level of combat where a variety of forces, systems, environments and activities, all simultaneously in force and at play, can create a picture of great complexity and confusion.

7.1 FRACTALS-LIKE ASPECT OF COMBAT (STRUCTURAL SELF-SIMILARITY)[5]

For the author, the first glimmer of the findings reviewed in this section occurred during preparation of a research plan for war gaming in (Low, 1981). Developing slowly over several intervening years, the ideas were given impetus by the effort to develop a theory of combat (DuBois et al., unpublished manuscript) and then somewhat belatedly by popularization of Mandelbrot's work with fractals (Gleick, 1987) and an eventual awareness of Miller's sweeping work in general systems theory (Miller, 1978). The last two developments reinforced a notion that the combat concepts could well be on track-or that, at the very least, there existed in the scientific community some independent evidence of a supportive nature.

In modeling warfare, the individual combatant is the smallest, single, living entity of interest to be found. As in the real world, all forces of whatever size or configuration are made up of these single entities interacting with weaponry, sensors, displays, vehicles, etc. Of major importance is a clear scaling and similarity of key (force) systems components and their associated functions across a size spectrum from the smallest force entity to the largest and most complex of forces. Applying fractals to the form and function of military forces seems to express a universality of component functioning for such forces regardless of size, all of which can be most encouraging to investigators in combat theory since it reflects the existence of some fundamental order in a seemingly chaotic process. This universality is observed in a hierarchical structure of force units in

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5 "We say that an object-a geometric figure, for example-is invariant with scaling, or self-similar, for short, if it is reproduced by magnifying some portion of it." (Schroeder, 1991).

which larger units are invariably made up of discrete smaller ones. Table 1 expands upon this idea.

The functions in the first column of Table 1 are derived from the major elements of Figs. 2 and 3 and the "aggregations" of Figs. 4(a) and 4(b). In the second column are the force components that carry out the specified functions (further described in Section 6.2 for all echelons of command). The third column lists subsystems of the human system that perform scaled equivalents of the functions in the first column. We inductively conclude that all of the trappings of warfare-military forces with their manpower, hardware, software, and support elements-are constituted and organized to serve as extenders to the capabilities of the individual human being in matters relating to deadly quarrels. This idea has been expressed by others in more general terms; in fact Miller (Miller, 1978) greatly expands on the theme to include all functions of living systems from the cell to the "supranational" (global) system of living beings. Employing this approach in the modeling of combat affords a stunning change in perspective that makes an extraordinarily complex problem seem a lot simpler. It may not make the model building *per se any* easier since there are many things about the individual human that we still cannot model or simulate. However, it does point up the things our models of combat should include for realism and for completeness. If they are too difficult to implement, we should at least recognize that they are not included in our models. Of most significance, perhaps, is that the approach may facilitate useful cross-fertilization among disciplines (particularly in the behavioral and natural sciences).

Table 1. FUNCTIONAL CONSTANCY WITH FORCE SIZE

	"Force" Components	
Function/Action	**Composite Force (All echelons)**	**Individual Human Combatant**
Command Control (leadership, perceptions, decisions, doctrine, directives)	Commander, Command staff	Brain (cerebrum)
Communications	Communication nets, systems	Somatic nervous system, larynx, hands
Combat/Active fighting (fire, maneuver, electromagnetic operations, interdiction and disruption, deception and masking)	Combat forces	Muscular system, skeletal system, limbs, hands, feet, teeth, brain (cerebellum)
Information/Intelligence acquisition (data fusion)	Observers, scouts, sensor systems, displays	Senses (sight, sound, taste, smell), somatic nervous system, brain stem, cerebellum
Logistics/Support (manpower and materiel support, movement, engineering, medical support)	Logistics/Support resources	Cardiovascular system, respiratory system, digestive system, immune system, autonomic nervous system, brain stem, food, clothing, medicine

7.2 FURTHER INVARIANCES IN MODEL STRUCTURE

Another finding from earlier theoretical investigations was that to the level of abstraction being used to describe combat model structure (Figs. 2 and 4), the question of whether the combat occurred on land, sea, or air or across domain boundaries (as surface-to-air or air-to-ground) mattered little. Even the transition from conventional warfare to chemical, biological, and thermonuclear warfare does not alter the basic model structure. This is not to say, however, that the *actual modeling* of combat forces, systems, environments, functions, and processes won't change drastically-it most certainly will. Furthermore, even though there is symmetry of structure around friendly and enemy force types and their actions, there can be great differences (asymmetries) in their combat behavior that stem from differences in respective contextual factors, initial conditions, and the model coding that emulates their performance in the real world.

Should the inductive hypotheses hold up under continuing scrutiny, we will indeed have established the universality of combat structure under a wide variety of differing warfare dimensions and conditions. While this is certainly a boon to theory development, it also provides a formalism for models and simulations that more clearly allows us to account for similarities and differences in the mathematical representations of many forms of warfare. Again, we find a degree of prevailing order within the intricate structure of combat.

8. MODELING'S TROUBLESOME LINKS TO REALITY

In Sections 1-7, we outlined a general framework for combat models with scattered observations along the way as to how some of the concepts discussed affect the real world of model building. There are, unfortunately, additional problems with combat modeling that should be addressed if this paper is to present a balanced, comprehensive view of the subject. Much of what follows stems from the practitioner's vantage point when using models to find solutions to specific military problems. From that viewpoint, it is the problem that will invariably constrain the way a model is to be configured.

We have established that combat is at least a two-sided activity,[6] and that, with decision-making freedom on both sides, it qualifies as a game. More precisely, in game theoretic terms, it is a dynamic two-person (or n-person), non-zero-sum game with multiple simultaneous action loops employing feedback control based on imperfect information. The action loops with feedback are the heart of the combat model and are exactly what has been described in Sections 4 and 6. A further layering of complexity called for in optimizing command decision-making using game theory principles often succeeds in pushing the problem beyond the limits of tractability (within the present state of the art of analysis).

There are models used in analysis, particularly in connection with product or system research and development, where the military system under investigation is modeled in its operating environment against an enemy with fixed, preplanned responses. As our candidate system parameters and operating modes are varied for exploratory purposes, the relative differences in outcomes for the encounters are noted (all against the fixed threat) and from such results we ascertain how best to proceed with system improvements. Quite obviously, this is a flawed methodology that could have serious consequences. In the freedom of the real world, an enemy would adapt (to the extent he could) to offset improvements in friendly system design, employment, or both.[7] As noted

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[6] Technically, of course, there can be and often are more than two sides to a conflict. However, these invariably settle into two-sided situations involving alliances or coalitions.

[7] Exceptions to this statement exist for those instances where fast, offensive enemy action constitutes the threat (e.g., tactical ballistic missile launchings, air strikes) and there is little, if any, time for evasive or exploitive changes to the enemy tactical plan.

throughout this paper and for the remainder of this section, we focus our attention on the unconstrained, two-sided combat problem as most representative of the real world while encompassing all of the more constrained decision-making options as special cases.

8.1 SCALE AND GRANULARITY

We will note at the outset that high resolution in modeling corresponds to fine granularity and low resolution implies coarse granularity. Furthermore, there is a direct coupling between granularity and level of aggregation, discussed below (Section 8.2).

To state it in the simplest terms, given the scale of the conflict to be modeled (determined by geographic area and/or size of forces and number of systems involved), it is available computing power and capacity (CPU time, storage) that dictate the feasible limits of model granularity and level of aggregation of systems and forces to be used. There are, additionally, instances where the resolution or granularity of available technical input and operating data for systems of interest will limit the level of detail to which systems are modeled or simulated. Principles of tidiness associated with modeling as an art form would seem to dictate a consistent, uniform level of granularity for each of the forces/systems being modeled, although a precise definition of granularity level applicable to diverse systems is hard to come by. Thus, judgment calls and subjectivity come into play over this issue in model building. A further cautionary note is in order; the measure of effectiveness (MOE) or performance (MOP) selected in the analysis of a system must be at a level of detail commensurate with, and supportable by, the granularity used throughout the model employed.

In this connection, there are instances when it is thought desirable to model a system of interest in relatively great detail against an environment/threat backdrop of coarser granularity so as to explore a system MOE to some particular high level of detail. The coarse backdrop is used in the model to shorten computation time, or to accommodate computer performance limitations, or both. The justification for such imbalance between system and environment resolution is that relative changes in effectiveness when we explore variations in system parameters should remain essentially indifferent to our use of fine- or coarse-granularity "backdrop" modeling. Reliance on relative rather than absolute values for our MOEs emphasizes the prescriptive rather than the predictive use of models. The latter most particularly must await further efforts in the area of model validation (see Section 8.5).

A final observation to be made is that large-scale conflicts, which might normally be forced to coarse granularity by computer size limitations can, under circumstances where the process couplings are weak, be decomposed into separate models developed to finer granularity. The separate models can be run independently, with results to be interwoven at some later stage of analysis. A typical example might be that of theater-level warfare involving at least one long logistic pipeline operating at capacity in support of either friendly or enemy forces. Here we can model the pipeline or line of communication (LOC) with whatever interdiction the enemy can achieve and measure the build-up of resources over time in-theater. Another model can be developed to accommodate the in-theater fighting processes with drawdown of manpower and materiel resources called for at appropriate times to be compared with stockpile results from the logistics model.

We can see, from much of the above discussion, that we are dealing with guidelines to model building that, while creative, are highly subjective, intuitive, and lacking in scientific foundation. This, unfortunately, is true of many of the issues discussed in the sections that follow. To resolve them in a more rigorous, scientific manner will require further extensive efforts in combat model development and in model validation.

8.2 AGGREGATION AND DECOMPOSITION

The topic of aggregation, as already noted, is strongly tied to the preceding discussion of granularity. When aggregating force or system units we are, for ease and convenience of analysis, taking the performance, location, and movement of certain smaller entities and combining them into fewer clusters of larger entities, each of which has modeled combat behavior equivalent to the cumulative behavior of its component entities. (Quite often, this is much easier said than done.) Cluster spatial coordinates and movement rates are made to approximate or to reflect in some ways those for the component entities. With higher aggregation (and coarser granularity) comes a lowered need for having to track the interactions of large numbers of model combat and support units in the computer codes.

Taking the single individual combatant with weapons and equipment as the smallest manpower unit of interest and considering for the moment a computer with unbounded processing capability, it should be possible to model force-on-force activity of any size by combining the one-on-one activities of all individuals in the opposing forces. If the individual activities are simulated with care and the command control networks and structures are modeled faithfully, as we combine smaller units into larger ones, we should expect to develop an accurate *combat performance* picture for larger, heterogeneous force units under the particular specified set of circumstances relating to threat, environment, and combat intensity and the component force operational reactions thereto. These larger aggregated units with their aggregated characteristics could then be used in subsequent analyses as long as the combat circumstances remain relatively unchanged and the granularity of aggregated forces is commensurate with that of the effectiveness measures being sought. Thus, in modeling land warfare, for example, we find it conceptually possible (given computers of limitless power) to move up the military organizational ladder from squads, platoons, and companies to corps and armies by integrating the performance of individual combatants on both sides, operating with the diverse equipment at their disposal.

In land warfare, it is the freedom of action of individuals and the increasing nonhomogeneity of force composition as we aggregate (e.g., infantry, armor, artillery) that makes this form of warfare the most difficult to model. Methodologies for aggregating forces in land warfare, other than by some laborious scheme such as we have outlined, are all suspect. Clearly this aggregation hinges on spatial and temporal relationships in combat of smaller interacting entities that vary in configuration. In modeling from the bottom up (from small units to large), aggregating forces and their combat behavior, we can identify and account for these spatial and temporal relationships and can then perform the aggregate summations. Those summations, as noted above, will very much depend upon combat event paths and circumstances. Conversely, if we start with performance data (e.g., kill rates, rates of advance) associated with mid-size to large units (such as battalions, divisions, or corps) *we cannot decompose (or disaggregate) the data to reflect the performance of smaller, component units* (such as companies or platoons). This is because we generally do not have an audit trail of interaction activities and circumstances that pertain to the higher-level force data.

The ability to aggregate from the bottom up while not being able to disaggregate from the top down would, in some sense, channel model development into the one-way street of bottom-up simulation of from smaller to larger force units. One must keep in mind, however, that the aggregation process requires two major prerequisites for its implementation: the availability of appropriate higher-resolution data in sufficient quantity to permit valid aggregation and knowledge, in a military sense, of a meaningful direction in which the aggregate summation should be made. While the first prerequisite does indeed militate in favor of bottom-up model development (and we are quite short of reliable knowledge in this area of aggregation from small to larger forces), the second prerequisite points to a need for a top-down look at the modeling problem (a "command's-eye view") to provide the contextual perspective for combat, the sense of mission, and definition of the hierarchical structure of organization and command for both adversaries. It is important, of course, that there be total consistency between model structures associated with both approaches with well-mortised joining at the boundaries between the two, wherever these happen to fall.

There are indeed factors that militate against the smooth and trouble free aggregation of forces in combat modeling. Here existing problems can be attributed to a forced compounding of poorly understood nonlinearities that, for the most part, can only be assumed away. An example of this is the apparent existence (in the real world) of "internal friction" in combat forces-a falling off of unit combat performance-as smaller forces are combined into larger ones. Broadly stated, this phenomenon most likely derives from a disproportionate expansion of command and control complexity with larger forces that cannot be expressed in explicit analytical terms. Hence, if friction is to be treated at all in modeling, we must resort to historical battle data (see Section 8.4).

We've alluded to difficulties with land combat models. It is perhaps fortunate that modeling naval and air warfare is somewhat less formidable. In the latter instances, vehicles and/or weapon platforms usually become the smallest combat entity of interest for purposes of modeling and analysis. Aggregation now comes into the picture more naturally. In certain cases of naval warfare, for example, personnel numbering in the several of thousands are all constrained to move as a unit within a single ship's hull. However, this "people aggregation" by vehicle will, of course, vary widely as we shift from, say, fighter aircraft carrying one or two crewmembers to missile cruisers, aircraft carriers, or cargo/transport aircraft loaded with combat personnel.

On a different note, perhaps, but also contributing to relative ease of modeling is a heavier reliance on functional automation in naval and air weaponry with less direct involvement of troublesome human factors (see Section 8.4). This is particularly true when combatants are using standoff guided munitions at sea or in the air; much less so if they are engaged in close air-to-air combat for example, or submarine warfare. In such cases, the terminal end game to be modeled becomes tactically complex, with demands made on all degrees of vehicular freedom, offsetting possible model simplification due to automation of weapon system operations. Furthermore, in the duels that occur in submarine and anti-submarine warfare, the oceanographic (geophysical) environment plays a dominant role in systems performance and presents the model-builder (as it does the submariner) with a wide variety of challenging problems.

8.3 DETERMINISTIC VS. STOCHASTIC MODELING

This section addresses another important issue in combat modeling around which philosophical differences continue to swirl. Basically, it concerns the efficacy of using deterministic equations or algorithms (implying that the workings of a process are known with certainty or a high degree thereof) when modeling a phenomenon as fraught with uncertainty as is combat and stochastic techniques are available for such problems. Perhaps more important, the discussion provides an opening for broader consideration of the significant sources of uncertainty in combat and how we fare in coping with them in our modeling practice.

That combat is an uncertain process is axiomatic (Hughes, 1992). Outlining a framework for the phenomenon in Figures 2 through 5 makes it possible to discuss a breakdown of the many sources of uncertainty in a structured manner. Discussion in Section 5 showed that virtually all activity in and around the combat arena is interactive to varying degrees. The fundamental interactions that prevail, summarized in Figure 6, center around activities that are either cognitive or physical (or both). The interactions are further defined in Table 2; however, the treatment presented here is by no means exhaustive.

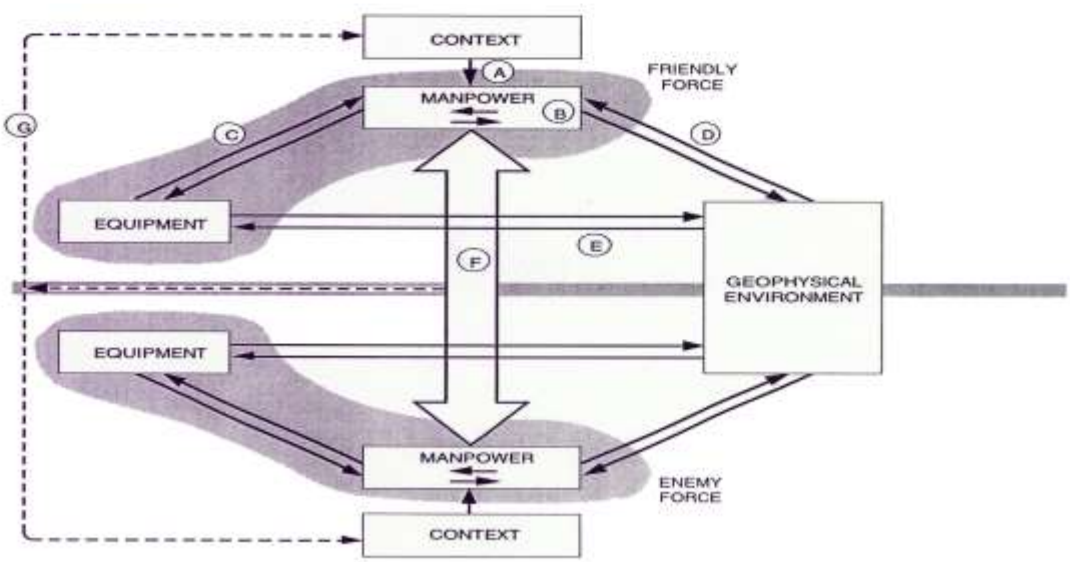

Figure 6. Fundamental combat interactions

Every interaction carries some baggage of uncertainty. Table 2 provides some idea of the cascading and compounding of uncertainty that occurs as we consider the various components of the combat process. At this point, we pause to identify the two main parts of the problem of assessing combat uncertainty: the uncertainty of the combat phenomenon as we experience combat and observe it in the real world, and the uncertainty associated with attempts to model the phenomenon, an endeavor in which we continue to find ourselves quite limited.

Table 2. MAJOR COMBAT INTERACTIONS

Interaction Category	Identification (Fig. 6)	Nature	Activities (Figs. 2, 5)
Combat context–force	A	Cognitive (largely)	Prior training, readiness, commitment, motivation, sense of mission
Internal to force	B	Cognitive, Physical	Leadership, discipline, mission (operations plan, operations orders), information gathering (intelligence, own force), information processing, estimate of situation, command decision, force control, force movement, force supply and replenishment, engineering/medical support
Man-machine	C	Physical (largely)	Weapon platform/vehicle operation, weapon selection/designation, target detection/ identification, designation, tracking, weapon firing/release, guidance, damage assessment, transport/construction/medical equipment operation, data processing/display interfacing, communications equipment operation
Man-environment	D	Physical, Cognitive	Effects of weather, climate, extremes of operating domain (e.g., terrain, altitude, sea state) on manpower performance, use of environment for detection opportunity, surprise, concealment
Equipment-environment	E	Physical	Effects of weather, climate, operating domain on equipment availability, performance; environmental changes resulting from equipment operation
Force-on-force	F	Physical, Cognitive	Total external force interaction with opposing force, concurrent with A through E (maneuver, attrition/destruction, deception, suppression, disruption, etc.)
Combat results–context	G	Cognitive (largely)	Effect of combat on national goals and objectives, will to fight, etc.

Combat can be characterized as a string of events over time involving two adversaries where the final outcome is usually sensitive to the event-result[8]/time path followed over the combat episode. There are arrays of alternative courses of action that can be taken by adversaries at many points in time in the game (corresponding to decision nodes) and the selection of any particular action at a point in time defines a singular event result-time path for the remainder of the game that affects the final combat outcome (see Appendix C). Actions taken by adversary forces depend on command perceptions of the results of previous encounters which, in turn, depend on the inner workings of myriads of other lesser events occurring both within and between forces. The actions taken reflect the command and control capabilities on both sides, running the gamut from rational command decision-making (good through bad) to the pathological, with varying degrees of force control ranging from close to loose control to, perhaps, none at all.

This description obviously portrays a phenomenon that is multilayered in its complexity and uncertainty. In concept, at least, much of it can be modeled using simulation techniques and principles of statistics and probability. If we concede to predictive models of warfare the highest potential for analytical utility, we find in practice, that significant obstacles stand in the way of their development even when conformance with accepted scientific procedures is less than adequate. These are the difficulties:

1. There are important parts of the combat process that we still do not understand in a quantitative, interactive way well enough to be capable of modeling them by any means. This situation holds despite the fact that theorists have written about them, they have been observed historically, and can be analytically addressed in a descriptive fashion. Our inability to model is particularly true of cognitive activities and their impact on the conduct and outcome of war. Can these effects be quantified? Exactly how important are they and under what conditions?

2. Even granting an eventual better understanding of combat's interactive maze, we lack analytical techniques that are reasonably practical, workable, and valid for modeling man and the complexities of his decision-making, that would allow us to replace him in man-in-the-loop situations.

3. Even granting success of efforts to develop adequate modeling techniques, the lack of data is cause for real concern, particularly the behavioral data and

8 Where event results are measured with respect to some single or composite factor, invariant with time, related to the combat.

systems statistical data that truly satisfy the context and input needs for modeling purposes.

We recognize, of course, that (1), (2), and (3) all require concurrent attention as they do trade off against each other. Also, all developments in (1) through (3) must ultimately be carried out under the umbrella of a reasonable model validation program.

Enveloped as we are in uncertainty, it is worthwhile to examine stochastic process modeling more closely. In this discussion, our interests are mainly focused on predictive modeling as a goal. However, we first will focus on a more structured description of what is involved in the "prediction" that is implied with such modeling. To start, we need only postulate the existence of a model that accommodates the context and circumstances of a combat (past, present, or future), the physical environment, the command structures, forces and weapons and their operations and procedures ... in short, all of the model factors discussed in Sections 4 and 6. "Prediction" would require that the sequence of events, as determined by the model, event timing, and the interim results as well as final outcome (qualitative and quantitative) and combat duration all bear a reasonable one-on-one resemblance to their past, present, or future real world counterparts in an actual play-out of the combat situation.

There are two distinct components to the prediction process. One has to do with how well we are able to forecast some future combat or how well we truly understand past or present combat with respect to all of the details required for purposes of predictive modeling. In short, we are addressing matters that reflect on our organizational capabilities to perform certain data collection, research and "intelligence" functions and we are quick to note that herein lies a good share of the overall process uncertainty. While this is particularly true for combat situations postulated for some time in the future, we must note that even battle histories do not always yield data that are Wholly reliable or that generally exist in sufficient detail for predictive modeling.

The second component of prediction reflects an ability to model "realistically" to any given set of combat conditions (that presumably might reflect a situation of interest). That is, when given such a set of conditions, the model will correctly predict the outcome of the encounter, thus establishing the model as a reliable "if-then" construct of cause and effect relationships. Needless to say, there are many uncertainties exclusively associated with this second component of the prediction process and it is with these that we are chiefly concerned in the ensuing discussion.

Let us return to our hypothetical computer (Section 8.2) of unlimited processing capacity and further stipulate the availability of a valid combat model of finest granularity (highest resolution). Further expanding on our fanciful conjecture, let us suppose that our model captures, in mathematical form, all of the behavioral characteristics and performance of either "typical" or specific sets of human beings participating in a combat episode. Where physical activity is concerned involving equipment, we postulate the ability to model interactions down to the finest details such as tracking missiles and projectiles along their flight paths and trajectories, which depend on atmospheric conditions and propellant performance, or the detonation pattern of individual fragments of a warhead against the target to which it has been directed, which in turn depends on warhead design, target aspect, and relative velocities. Fragment damage to the target would be tied to specific degradation of target performance, and so on. It is stipulated that all of this is known with enough precision to allow it to be modeled with a collection of deterministic equations or algorithms. If we were to run a combat situation with this model many times, under identical sets of inputs and initial conditions, it is interesting to speculate on the statistics of the outcome (defined in some specific way). Obviously, we can only conjecture, since this experiment has never been conducted, nor is it likely to be in the foreseeable future.

With a deterministic model of unlimited detail, as described, it would seem that all reruns of the model under *identical* start up conditions should produce identical paths of event-results over time and identical final outcomes. Again, we emphasize that the model being discussed cannot be realized (most particularly with respect to the emulation of human behavior). This, however, is not a crippling setback for in the quest for a modeling representation of reality there is little, if anything, either in nature or science, that is strictly and purely deterministic-least of all, in the sociotechnical *mélange* that characterizes armed combat. Take, for instance, our example (above) of warhead fragmentation patterns; if our model had accommodated impurities in warhead materials at the molecular level or flaws in warhead manufacture, we would have obtained a different fragmentation pattern with the warhead detonation in successive replications of the game (all things being equal), yielding differing degrees of target damage or destruction. This is an event-result change that can produce changes in human decision-making at various decision nodes and command levels that may, in turn, exacerbate differences in event-result/time paths among game replications and thereby create significant variation in final combat outcomes. Thus, even the modeling of physical activities in combat, when carried to the deterministic extremes postulated in this discussion, could produce variable results if relatively minute variations in equipment material, manufacture, and performance were treated explicitly within our purely deterministic methodology. Adding the human element with its cognitive activities only drives the stochastic behavior of our combat modeling to wider extremes.

It is the statistical distribution of combat outcomes (their mathematical form and moment parameters), where outcome is scaled to some measure of merit, that constitutes the item of greatest importance to the model user. To the military mind, however, there is an inescapably hollow aspect to the prediction that may involve a wide distribution of outcomes for a battle or engagement that will be fought only once, even though this may be the imperfect best that science can offer in the face of so much problem complexity.

In passing, we should note that in hypothesizing the above, we seem to be nibbling at the edges of a chaos theory application to combat modeling-something perhaps akin to the Butterfly Effect or a "sensitive dependence on initial conditions" (Gleick, 1987). In the present situation, though, it is more aptly a sensitive dependence on the stochastic contamination (however slight) of attempts at a pure deterministic approach that, when coupled to attendant discontinuous shifts in decision processes, further contribute to the statistical spread in combat outcome. All of this presupposes that we could develop nonlinear models to the degree of detail that has been described (which we must disavow). The relationship of chaos theory to combat modeling, currently under investigation by a small but dedicated group of researchers, is considered beyond the scope of this paper.

Constrained as we are in modeling by available techniques and data, how do we normally proceed with model construction? As already noted, there is a distinct trade-off between dynamic process modeling and the direct input of information into a model (presumably based on valid data), as in the case of simulating all of the fragments of a detonating warhead against a target instead of simply specifying a kill probability of the warhead against the target. These inputs can be defined as constants or variables and, furthermore, they can be deterministic or probabilistic in nature. Clearly, process modeling is the richer, more complete, and more informative representative of combat activity that affords deeper insights into the inner workings of a complex, dynamic system. However, there first must be an adequate understanding of the process being modeled. When such understanding is lacking (as in many cognitive processes), we resort to the lumping of behavior or performance into a statistic (i.e., the probability of a specific occurrence) that may jump over numerous cause-and-effect steps that we know little about. Or, we can use the lumping technique to simplify our models and shorten computation times even when process modeling is a feasible alternative. However, for a valid methodology, the statistics used should be derived from observations, exercises, or experiments that can be related to the combat circumstances being emulated-the only scientific basis for determining input values to be used. In general, statistical measures should include the forms of probability distributions, their means, and their variances. Seldom is the proper degree of attention afforded preparation of these input data.

We can now converge on a position for predictive modeling that logically emerges from the foregoing discussion. As already indicated, there are important quantitative aspects of combat that are little understood and warrant serious investigation; there are large voids in modeling technique, particularly for behavioral phenomena, and there are generally vast shortfalls in statistical input data required for stochastic modeling. That we are involved with a structured, albeit a highly stochastic, phenomenon is clear. This phenomenon has so many layers of uncertainty that combat outcome distributions, particularly under conditions of near-parity between opposing forces, can be exceedingly broad, leaving those who are analytically oriented with little in the way of clean, dominant "win-lose" criteria upon which to base some aspect of military planning.

In essence, we are saying that the predictive use of combat models logically evolves around realism in modeling and the use of stochastic techniques is called for to permit achievement of such realism. As a consequence, and most unfortunately, the predictive use of models is still a long way from being realized for the several key reasons given above. This, however, rather than being cause for despair, should spur a redoubling of long-standing efforts at model improvement (along lines discussed above) with a better organized, more focused, and more cohesive research approach. At the very least, we should be pursuing development of valid, provisionally predictive models of the "if-then" variety. This might be accomplished through a two-way program of building models to match selected controlled experiments, while progressively ironing out discrepancies that appear between the two. Until we take deliberate steps to validate modeling efforts against some form of reality, we cannot lay claim to a scientific methodology for predicting the course or outcome of combat.

The absence of prediction capability has ramifications for the model applications discussed in Section 2.0; specifically, those concerned with estimating force levels and support requirements. These estimates, to the extent they are based on models, are closely tied to absolute rather than relative model results as appropriate force parameters are varied in the analysis. It is unfortunate that such absolute measures remain beyond our grasp. Nevertheless, we retain a lot of the utility inherent in applying models of combat to military problems even though we are forced (by the lack of scientific knowledge and methodology) to deal with the relative outcome measures. In so doing, we underscore a tutorial attribute of modeling: that of providing insights into problems of great complexity. This attribute can be put to use when applying models to areas of military education, training, and systems development. Here it would seem that deterministic models (hopefully accredited or validated in some manner) could, in certain circumstances, provide useful relative results that would signal preferred operational procedures or point to worthy directions for technical development. This constitutes a use of modeling more prescriptive than predictive and also applies to state-of-the-art stochastic models, imperfect though they may be.

8.4 MODELING HUMAN BEHAVIOR

This subsection addresses what is by far one of the most difficult, challenging aspects of combat modeling: the modeling of human behavior in combat while performing, at all organizational levels, the functions of:

- Command leadership and motivation
- Perception and interpretation of battle developments (including reactions to enemy surprise and deception)
- Decision making
- Promulgation/communication of orders and instructions
- Own-force monitoring and control
- Operating and interacting with all forms of equipment (vehicles, sensors, weapons, communications and countermeasures systems, etc.).

These functions are performed under conditions of active fighting and of support to the fighting forces. Since combat is fundamentally a behavioral phenomenon so heavily interspersed with so many forms of human activity, our above list is not likely to be exhaustive.

In modeling, human behavior has been traditionally coupled to combat in two fundamental ways. One is the implicit or explicit representation of decision-making (and associated functions) by both sides that established the game path for any particular run of a combat model. The other (tied to an earlier observation that outcomes of combat models are invariably measured in terms of physical-rather than cognitive-activity) attempts to estimate the effects of the cultural, sociological, and behavioral factors previously identified on human physical combat performance. In the first case, we can either have men in the loop to make the necessary decisions on both sides, or we can employ contingency logic in programming the model to stipulate "if [this] happens, then [designated forces] do that." This programming is an abbreviated set that constitutes stylized, built-into-the-model, "automatic" command and control. In the second case, traditional use is made of nondynamic judgmental/historical factors[9] (a form of "scores") that enhance or degrade physical performance parameters of engaged forces, such as kill rates or rates of advance, in accordance with force "state of mind."

There are, unfortunately, analytical drawbacks to each of the techniques mentioned. Inviting human participation in the game in any decision-making capacity plays more to the game's value as an instrument of training than as a predictor of outcome. In a game with player participation and a goal of outcome prediction with "generic" commanders, the depersonalization of decision-making will generally require many replications of game plays (with different sets of players) to accommodate the variability of both physical and cognitive activities during combat. This variability, for reasons already discussed, can be very high and the entire process of obtaining game results that are statistically valid is likely to be very unwieldy and time-consuming.

The alternative to man-in-the-loop gaming, that of preprogrammed contingency decisions in the models, while streamlining operational procedures in running the model, is cause for concern in that it will usually limit or constrain in a significant way the set of all possible decisions that could be made on both sides. This observation even extends to "expert system" databases associated with artificial intelligence that have been used with a measure of success in other scientific endeavors. Precious few combat experts are qualified to create in the abstract a comprehensive database for strategic and tactical decision-making in warfare. This is true largely because combat, as a phenomenon involved with "man against man (and nature)" is far more complex than the "man against nature" cases for which expert systems were first derived. Combat can be likened to an extended form of chess where pieces on the board are not consistently visible to the players and the identity (and value) of chess pieces can at times be misread by either side. In addition, both players occasionally suffer motor difficulties to varying degrees in moving pieces about the board so that moves cannot always be executed as planned. Clearly, it would be difficult to create a game-playing algorithm-or to find the expert-that can "optimally" select moves under such conditions of uncertainty. Thus, techniques that substitute for man-in-the-loop in modeling will currently (at least) restrict us in

9 An approach long-championed and supported in the United States by the work of T.N. DuPuy (1987).

representing the CZ function to partial sets of decision alternatives from which to choose. This may prove adequate when using models for purposes of system design or improvement, provided the model of decision structure most closely associated with operation of the system under scrutiny is essentially complete. Decision modeling for outcome prediction, on the other hand, calls for the more robust representation of force command and control on both sides.

Turning our attention to performance multipliers that relate to the behavioral variables of combat context, we obtain a certain measure of confidence and satisfaction from the fact that here is one of the few areas in combat modeling where we attempt to derive numbers from actual combat data. These data are largely historical in nature and are gleaned from accounts of past engagements. Some numbers, however, can be purely judgmental based on military and foreign affairs experience with some particular adversary. Both cases involve degrees of subjectivity[10] (more pronounced in foreign affairs than in military affairs). In this methodology, the concept of factors that modify the overall combat effectiveness of a force based on its psychological state makes an enormous leap across countless cause-and-effect barriers while apparently (and understandably) despairing of an ability to define or analyze them. Traditionally appearing as multipliers to force size or to Lanchester attrition coefficients, these factors exert a rather direct and perhaps exaggerated influence on combat outcome. From experience, we know the couplings they emulate to be very important in warfare, yet they are treated primitively or too often neglected altogether in combat models. They most certainly beg for a more formal, in-depth, methodology with clearer causal links and richer databases. These might afford dynamic variations of combat performance with changes in combatant motivational attitudes during battle.

In the final analysis, the best way at present to emulate the functions that humans perform in warfare is to have humans participate interactively in a simulation game. There are difficulties with this approach that have already been described and, additionally, we have the problem of having the players experience the effects of fear, anxiety, and confusion that prevail at times in actual combat. While the adrenaline flow accompanying these states may be partially induced by a carefully controlled game environment, the results will invariably fall short of what is observed in actual combat.

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[10] History, unfortunately, does not always record the information that is most directly connected to the data we seek. Therefore, we must draw inferences from what is available. Furthermore, the historical accounts themselves may involve some measure of subjective interpretation by their reporters or may be colored by political considerations prevailing at the time.

As battles and wars progress, linking the effects of initial and changing societal attitudes to the performance of the combatant forces remains a problem whether or not human players are introduced in the simulation. Obviously, the importance of this linkage depends on the duration and intensity of the fighting being modeled. As mentioned above, the "factors" approach (modifying physical performance) may be the only one open to us until extensive behavioral research can establish more direct causal relationships. Nevertheless, in the interim more rigorous ties of combat effectiveness to psychological state generated by societal attitudes or by battle itself should be explored based on the best available historical and experimental data.

8.5 MODEL VALIDATION

All paths through the maze of conceivable effort to improve combat modeling must inevitably negotiate the barrier of "validation." Being engaged in scientific inquiry, we must concern ourselves at some point with comparing the performance of our models against phenomenological evidence from the real world. In so doing, we would hope eventually to bring combat models and theories into conformance with "experimental" data. Given the structural complexity, the nature, and the uncertainties of combat, it is no small wonder that, as has already been noted in this paper, the task of attaining clear closure of model results with experiments borders on the impossible.

There are few sources of experimental evidence that can be considered candidates for purposes of model validation. These are:

- Military histories
- Combat experimentation
- Training and readiness exercises (field, fleet, air, joint)
- Systems operational testing and technical evaluation
- Ongoing warfare
- Other models and simulations.

Unfortunately, as we will show, none of these sources taken singly or in combination will squarely fulfill in a practical manner the validation needs for models of combat. They signify classes of experimental material relative to modeling that are a fall-out from endeavors conducted primarily for other military purposes. In this light, we can look upon them as possessing certain attributes relative to their validation roles-attributes such as format convenience, accessibility and cost experiment reproducibility, experimental control of combat and environmental variables and the extent of total combat operations coverage (as established by Figure 5).

We briefly review each of the techniques that have potential application to model validation with an eye to identifying their strengths and shortcomings in that particular role. First, however, we discuss in more detail what is meant by validation under such unusually complex circumstances.

Quite obviously, we cannot obtain correlation between theoretical and experimental results to a degree that is possible in the physical sciences. In fact, it behooves us to think in terms of validation levels where the uppermost, farthest-reaching (and unattainable) level would be the close matching of structures, dynamics, results-all aspects of the problem-for any set of combat conditions and any degree of model granularity. Drawing away from this extreme objective, we resort to considering piecemeal model validation, or components of validation, each of which constitutes an element of partial validation for a model. These components, which relate to material previously presented in Sections 4 and 6, consist of

- Model structural conformity and adequacy
- Command decision nodes and decision content
- Combat/support process accommodation (for attrition, suppression, maneuver, etc.)
- Adequacy of combat/support system performance algorithms
- Input accreditation (order of battle, systems, environment, and context variables)[11]
- Sequence and timing of significant events; combat duration.

Returning to the discussion of experimental techniques and their attributes for model validation efforts, we first consider history. Even though validation has never received the attention it deserves in some fifty years of serious combat modeling, it is still military history that is used most frequently, and has been from the days of Lanchester and Osipov (1914-1916) who first used historical battles in independent investigations to demonstrate the correctness of their attrition equations. Most particularly, since World War II a small, select group of investigators in the U.S. have attempted to validate low-resolution types of Lanchester models (attrition equations in closed form) against historical records with what must be described as mixed results. In general, attrition is the

[11] A role reversal of sorts often occurs with this component category in that we find model inputs are derived from experimental sources rather than being validated against them.

only process of several that have been identified (see footnote, p. 14) that is modeled by Lanchester's equations, and while broad trends of incurred battle casualties are mathematically described in reasonable fashion by the equations, it is far less so for the actual numbers of such casualties as functions of time. In fact, some of this historical work has been turned around and used to derive exponents (for a generalized form of Lanchester model) and to find attrition coefficients that will produce a closer fit of theory to historical experiment. Equations with these values can then be corroborated using other historical battles of similar scope and circumstances.

Historical results are relatively bountiful and accessible but are not generally available in a form, with a frequency, or for situations and conditions that validation of a specific model may require. Thus, we have no control over reproducibility of the "experiment" or its variables.

Furthermore, as we have noted, measures of subjectivity can well be involved in both the reporting of historical conflict and the interpretation and abstraction of data from such accounts. This is in addition to knowledge gaps, plain and simple, and to the cultural, emotional, or political attitudes that invariably flavor historical reports, making their reliability and accuracy open to question. Yet history is usually rich in contextual material relating to combat that extends to the strategies, operational art, and tactics governing its conduct. Thus, we find history rating high marks in providing wide operations coverage for purposes of model validation.

We next turn our attention to various types of experimentation as a means to meet validation objectives. Thus, we now focus more sharply on activities expressly conducted in a mock-warfare environment to train troops, to develop tactics and doctrine, or to learn more about the technical and operational characteristics of new systems hardware. Precious few, if any, experiments are conducted solely for the purpose of validating models, so that if validation needs are to be met they must be piggybacked onto exercises and experiments designed to investigate other military capabilities. Therein lies a good bit of our existing difficulties with validation in that, until rather recently, commands vested with military experimental or exercise responsibilities for singular purposes were not overly accommodating to the needs of analysts and modelers. Now there are changes in the wind that seem to favor the collection of necessary additional data to permit reconstructions of experiments and exercises in enough detail to assist with model development and validation. Such procedures should eventually produce a better understanding of the full depth and breadth of the validation problem and perhaps progress towards its solution.

As a general rule, the types of experiments under discussion are relatively elaborate undertakings that would be considered costly and cumbersome were they to be used only for modeling accreditation purposes. Since they involve range facilities with special equipment, a variety of personnel and, at times, large numbers with associated weapons and military hardware representing both friendly and enemy forces, it is not surprising that experiment reproducibility and control of combat variables would be poor in a purely validation application. Yet there are recent trends toward the selective conduct of experiments that are designed exclusively for, and can be run in parallel with, certain "if-then" model constructs. Such efforts could lead to the piecemeal validation of models that are provisionally predictive as described in Section 8.3 (p. 27).

The use of warfare as a "laboratory" in which to evaluate systems concepts and tactical hypotheses had rather strong beginnings within certain U.S. and U.K. commands during World War II, giving impetus to the establishment of operations research as a formal discipline. Subsequent wars in which U.S. forces have been involved (up to and including Desert Storm) have been witness to ever stronger, more elaborate analytical tasking during the conduct of military operations. These assignments have, among other things, been concerned with collecting combat data (qualitative and quantitative such as resource casualties and expenditures) and conducting "quick response" experiments on modifications to, or the alternative employment of equipment.

Specific tasking can be used to either generate or verify inputs to models, or to establish trends in battle outcomes with changes in tactics and equipment. However, uncovering any "great truths" of war must generally await the termination of hostilities and an examination of enemy plans and actions during the conflict. At that juncture, one could only hope for objective reporting of what had transpired on both sides so that an accurate historical record would be available for posterity. Clearly, use of warfare for validation is totally uncalled for were it not for having to engage in battle for other reasons. Even so, experiment reproducibility is virtually nonexistent and the control of variables is quite one-sided.

A summary of validation techniques and their attributes (subjectively rated) appears in Figure 7. In addition to the techniques discussed above, Figure 7 shows a sixth category, "Other Models and Simulations," illustrated separately from the left-hand group of five techniques. The first five techniques involve experimental formats that are tied directly, or nearly so, to the outcome realities of combat. The sixth technique concerns the comparison of models, involving members of the same format set as the model we wish to validate. Thus, a sense of "bootstrapping" is imparted to such an effort. When faced with the fragmented validation process being described in this section, this comparison of model outputs seems to be a most logical, relatively simple, first step. In partial compensation for being inconclusive for validation purposes, the approach does enjoy high attribute ratings as indicated in Figure 7. The figure illustrates (with the dotted arrows) the general dependence of models and simulations on direct experimental procedures for the attainment of higher validation levels. However, under such circumstances, the caveats and shortcomings discussed above will apply.

We now turn to a new development being pursued quite vigorously that, if successful, may revolutionize the conduct of training exercises and combat experimentation while, at the same time, providing for almost automatic validation of simulations (and simulators) through the interaction with live forces (men and equipment) in real time. This significant advance in concept stems from rapid developments in computer processing, graphics, and networking. It suggests the feasibility of distributed gaming wherein live forces, simulated forces, and manned simulators of equipment, not collocated, all operate in a synchronous mode ("seamlessly") in a common geophysical environment. The audio-visual aspects of the common environment are transmitted and presented at all stations using, where appropriate, techniques of advanced graphics and virtual reality. In short, the concept involves a methodology conglomerate of man-machine experiments amid a variety of simulations and simulators. Under such conditions, there is a forced validating of consistency of simulation with experiment, for the two types of endeavor clearly must mesh flawlessly in real time if the methodology is to prove feasible. This concept of experiment-in-the-loop is to the varied simulations of distributed gaming what man-in-the-loop has been to the traditional centralized combat simulation. In both instances, elements from the real world are being introduced interactively into the game. However, in the case of the experiment-in-the-loop, the benefits may be even more pronounced since the concept incorporates built-in validation measures.

By way of summary, we reiterate the applicability of material in this paper to all forms of combat models and simulations regardless of methodological composition and arrangement. For the present, model validation must proceed in piecemeal fashion to varying levels of conformance with evidence from the real world. The validation problem has three basic components: the use to which the model is put, the parts of the model to be validated, and the validation techniques to be used (with their varying attributes). With model usage divided broadly into prescriptive and predictive categories, it is the predictive model that imposes the most stringent validation demands. These are not likely to be met in the foreseeable future with any high degree of scientific rigor. Yet, we are obliged to continue research toward valid

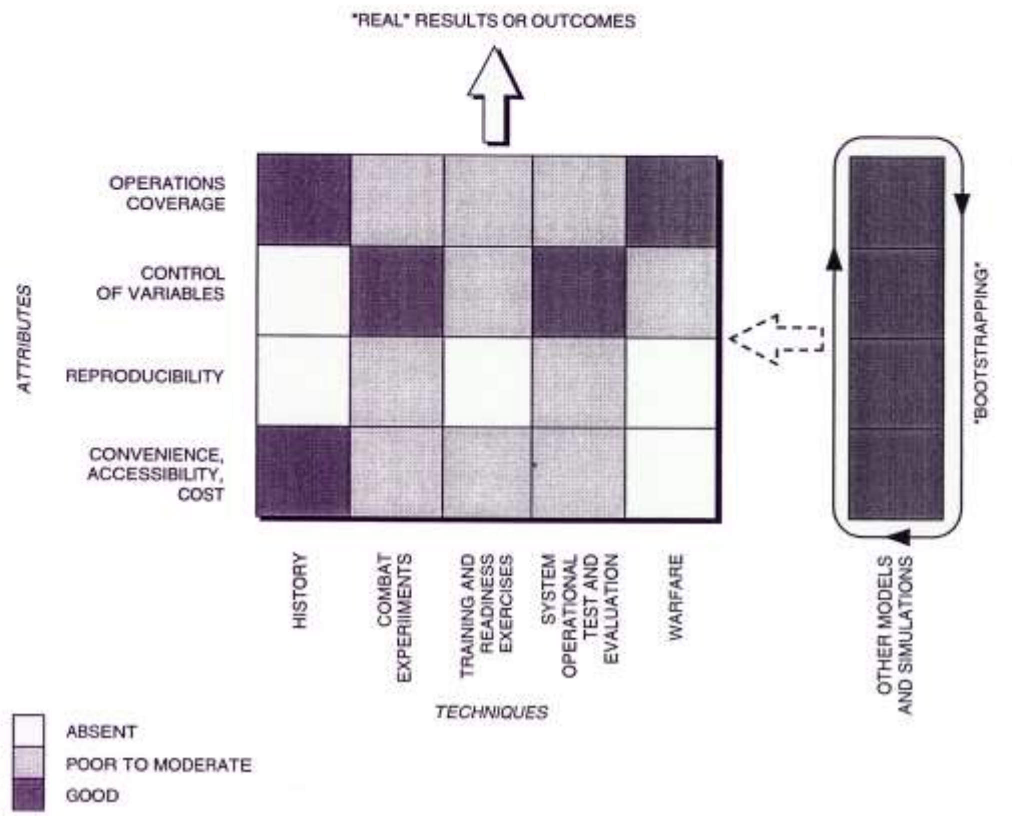

Figure 7. Model validation techniques and attributes

methodologies that address the systems, processes and environments of combat as an aid to military planning, training, and establishment of policy and the conduct of operations.

9. COMBAT MODELING WITH AN EYE TO THE FUTURE

In the preceding sections of this paper, we have discussed the combat model in rather broad, comprehensive terms, attempting to define such a model to a certain level of generality, describing how models can be used, and touching upon some of the issues associated with their more widespread acceptance as scientific developments. It is appropriate at this point to pause and consider the scope and complexity of the problem that confronts us when trying to establish wider credibility for the use of combat models as tools for military decision-making. Once that is done, we can sketch a program of investigatory steps that should lead us to some answers to our questions. No attempt is made to define a research program in detail. Instead, we summarize the combat problem, characterize it as a complex systems problem, and then proceed with the identification of major methodologies, techniques, or procedures that can further our knowledge of combat phenomena.

Despite too many models to the contrary, combat is primarily a *behavioral* phenomenon which, depending on circumstances, is influenced to varying degrees by the physical sciences and technology. It is precisely the behavioral aspects of combat that inhibit efforts at mensuration; in fact, most attempts to force the problem into some form of mathematical expression run into significant difficulties, as it is far harder to quantify human behavior in combat than it is to quantify the "hard" sciences.

If we cast the military operational problem of combat into a system-science mold, we find, in summary, that it has these general characteristics:

- It is a social as well as a technological phenomenon.
- It is concerned with deadly quarrels involving two (or more) sides, with unconstrained reactions to the limit of resources and ingenuity (as defined in Sections 3 and 4).
- Combat is episodic within the spectrum of armed conflict (from one-on-one duels to global warfare) with a reasonably definable "start" and "finish" for each period of combat activity.
- Opposing forces are mission-driven (generally in non-zero-sum fashion).
- Forces employ feedback control through C ^{3}1 functions (attempting to "zero out" error between "mission" and unfolding "combat results").

- Control is based on imperfect information and command perceptions of combat results.
- Major interactions occur among combat functions and processes involved with C^3I, active fighting and support for both (all) sides.
- Combat processes are generally nonlinear, stochastic, and exhibit patterns of chaotic behavior.
- Operational functions are characterized by self-similarity at all levels of the combat organizational hierarchy.
- An equivalence of combat functional structures prevails for both (all) sides in a combat regardless of warfare domain, scope, or intensity.

The view of combat upon which the above observations are based is not the only one. There well may be other structured ways of looking at the problem. For our purposes, however, the descriptive framework we've used seems to suffice; it is capable of accommodating the many facets of combat and it represents a synthesis of accumulated military experience and innumerable efforts at modeling building.

The highly complex system described by the above listing presents a most difficult modeling challenge (this, despite the possibility of simplifications afforded by the last two list entries). The structural complexity of the problem is additional to the prevalent need for large amounts of input information as discussed in Section 6. Unfortunately, much is often of questionable validity; valid information can be extremely difficult, if not impossible to obtain given our present state of knowledge. Under the circumstances outlined, how might we better our understanding of the entire combat modeling process? Certainly this must hinge on some deeper analytical penetration of the combat phenomenon itself.

In what follows, we recognize some interdependence between a model and the nature of the problem to which it is applied, going beyond the obvious matter of model fidelity. This extra measure of dependency derives from variations in problem-solving procedures that are determined by the use to which the model is put (Section 2), the techniques employed as part of the model-building methodology (Section 5), and the scope and intensity of the combat being modeled (from duels to theater and global warfare). Additionally, there are figures of merit (FOMs) or measures of effectiveness (MOEs) we would wish to use that relate, in turn, to whether we are modeling prescriptively or predictively.

For our present discussion, we dismiss the observation that "an all-purpose model is a no-purpose model." We assume that aiming for the highest goals of realism and predictive utility in model development will result in a product that consistently (but perhaps not efficiently) satisfies all of our lesser, more modest model requirements. Thus, we eliminate from the present discussion further consideration of the variations in modeling methodology that are tied to changing needs for "adequate" solutions to a wide range of military problems. We are sidestepping this issue for the moment only; it will be addressed again later in this section.

All of the above now leads us to a summary of significant issues which, for convenience, we will consider in three major, closely related parts. These are issues associated with the actual modeling of combat and its processes, issues associated with model inputs and data bases, and finally, overarching issues, transcending the first two, that are associated with models in their entirety.

9.1 MATH MODELING[12] ISSUES

In narrative form, our understanding of combat seems virtually boundless. It is when we attempt, in scientific fashion, to fit it into a system structure with the goal of applying measures to combat states and outcomes that our lack of a deep-enough understanding of the subject becomes apparent. This is manifested by difficulties we have in answering the following types of questions:

- Do we have access to a valid descriptive structure of combat (in this document or elsewhere) that reflects a sufficiently clear understanding and adequately addresses all important aspects and dimensions of the combat phenomenon?
- Given an understanding of basic combat structure, can we identify and track on-going processes in historical combat?
- Are there general patterns governing the degree of interaction among these processes?
- Can we identify those processes that, under specific circumstances and conditions, appear to drive combat results?
- Can we identify sets of key first-order variables that predominate within these driving processes?
- Can we identify suitable methodologies and analysis techniques that aptly model the action flows of combat and the combat processes we have identified?
  - What is the role in combat modeling for formal mathematical procedures such as game theory, control theory, Lanchester laws?
  - Under what circumstances is it appropriate to model combat in closed form? by simulation? by "man-in-the-loop" simulation? by computer-assisted manual gaming? or by computer-assisted combat experimentation?
  - How do some of the more recent developments in math modeling (i.e., chaos, catastrophe theory, fuzzy logic, neural networks, cellular automata, and virtual reality) enter the combat modeling picture?
  - Can any of the above be effectively brought to bear on the problem of modeling behavioral or cognitive aspects of combat activity?
- What are the forms and characteristics of the circumstantially dependent statistical distributions associated with the outcomes of stochastic combat models?

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12 Math modeling, as used in this paper, is defined to include the use in models of equations with closed form solutions, computational techniques such as linear or dynamic programming, and all forms of simulation.

Of foremost importance in seeking answers to these questions is how generally applicable these answers may be under varying combat circumstances. Would there be patterns to our findings? And are there ranges of applicable circumstances associated with the findings that are sufficiently broad to constitute useful laws of behavior for the variables and processes of combat? Surely efforts directed at exploring such issues could only further a deeper understanding of combat which, in turn, would significantly improve our abilities to model the phenomenon.

9.2 MODEL INPUT AND DATA BASE ISSUES

As already noted, a major methodology tradeoff exists between process (cause and effect) modeling and the direct inputting of data or information into a model where it is then subjected to further mathematical manipulation. All models, however (including equations encountered in the sciences) will, at some level, require input information. In combat modeling, the split between what is modeled and what is treated as input to the model is somewhat traditional (see Section 6.0). Values for combat contextual variables are relegated to input, including variables of the geophysical environment and initial-condition values for resource state variables on both sides. We would postulate that the information content using process modeling and the knowledge to be gleaned from such a procedure far surpasses that from operations performed on model input. The greater analytical depth of process modeling against the one- or two-dimensional character of input numbers or look-up tables generally make it preferable to employ process modeling to the maximum extent possible. Doing so, however, requires an intimate understanding of process (whatever it may be) that we often lack. In some sense, traditional model input is a fallback for this lack of sufficient knowledge about process cause and effect. If we do not understand a process in combat well enough to model it, perhaps we can find some measure through historical research or through laboratory or field experimentation that reflects the effect of contextual or environmental variables on combat performance of the engaged forces.

This now brings us to what may be one of the most serious deficiencies in all combat modeldom: bringing human cognition and behavior into what we've described throughout this paper as a behavioral phenomenon. To do so, we must bridge the enormous gap that lies between contextual cognitive and behavioral variables that we know from experience influence combat outcome and the *processes* of combat (physical *and* cognitive) whose interactions tie directly into combat results and outcome as shown in Section 4.2. At present, our understanding of cognitive processes (such as demoralization, disruption, deception, etc.) is insufficient to allow us to model them explicitly. We also lack the ability to *quantify* a host of cognitive contextual variables as well as to express explicit relationships between these variables and the combat processes that forge the links between model input and output. In short, what we are left with in combat modeling is the capability (although it is imperfect) to treat the *physical* performance of humans and their weaponry while our understanding of the human mind and its thought processes is too shallow to be compatible with explicit modeling procedures. Thus, the very core of the combat problem goes begging for adequate treatment in the modeling world while, by continuing to focus on the physical aspects of combat, we look for the proverbial lost keys in the light directly under the street lamp.

There are fallback positions (beyond man-in-the-loop gaming) that we can adopt to circumvent these difficulties. From historical data or intelligence estimates, one might derive as input to a model certain "factors" (multipliers) to be applied to the physical processes (such as attrition or movement) through their variables to couple cognitive contextual variables and combat outcome. In the absence of "real" data, such factors can be selected judgmentally. Short of these alternatives, our choice, made all too frequently, is to omit this aspect of combat altogether from our models. Little in the above approaches to the problem can be viewed as inspirational.

Additional concerns about inputs and databases for the most part revolve around the derivation and validation of all forms of input data (whether physical, cognitive/behavioral, or other). The material in Section 8.5 addresses this topic for combat models in their entirety but also applies to the input/data base segments of these models. These are difficult areas, in which the lack of sufficient information and depth of knowledge impedes any scientific approach to modeling.

9.3 OVERARCHING MODEL ISSUES

We next turn our attention to issues that transcend those related solely to mathematical process modeling and those related to data that are the boundary conditions and inputs to a model. First there is the question of the tradeoff balance between the two major components of model design, recognizing (as already stated) that data, if available and properly used, can substitute for process modeling. How much of the model should be cause-and-effect process modeling and how much should consist of operations on aggregations of data input? Unfortunately, the answer will depend to a significant degree on the use to which the model is to be put, as discussed in Section 2. Are, for example, prescriptive attributes of the model adequate for the problem at hand (with MOEs based on relative outcome values) or are predictive qualities called for (as in the case of MOEs based on absolute outcome values)? While we may look for balance under ideal conditions, in practice the tradeoff between process modeling and direct input manipulation is often a matter of necessity. The extent of the tradeoff is dictated by the degree of our knowledge (or lack thereof) about certain combat processes measured against the availability and reliability of surrogate data that could serve as model input. All of this discussion is predicated on the assumption that the "molecular" model of Section 8.3 is "best" for the information and insights it provides and, all other things being equal, is the goal to which we should aspire.

Another matter of concern is the need to learn more about the relative impact on "measured" combat outcomes of systems technology as compared with that of combatant behavior under varying combat conditions and circumstances. Doing so will bring out the greater depth of knowledge we have of technical matters and their related physical processes in combat over that which we have of the cognitive and behavioral areas. Two unrelated trends with somewhat conflicting implications for modeling seem to be evolving at the present time. One trend, which complicates modeling, is the realignment of competitive and cooperative national power blocs throughout our world from a structure that was, for almost fifty years, predominantly bipolar to one that is far less clearly defined and consistent. The other trend is toward ever-increasing automation in man-machine systems.

Realignment has led to lesser crises worldwide that stem from a gamut of causes (e.g., economic, political, ethnic), and from a variety of natural catastrophes. Some may call for U.S. military intervention in what are mostly humanitarian or police actions (operations other than warfare). These activities are in possible concert with one or more allies against single antagonists or hostile coalitions. The context of combat (Section 6.1) can become extremely complex, throwing heavy emphasis on external contextual factors that can easily have as much impact on conflict outcome as the actual fighting. Many of these factors are associated with human behavior and cognition.

Proceeding in parallel (although unrelated) is the simplifying trend within man-machine systems of the combat arena toward ever-increasing automation in areas of decision-making formerly reserved for human beings. Involved are systems providing command decision aids for battle management, decision-making in systems for reconnaissance and surveillance, intelligence data processing, target acquisition, designation, and weapons assignment, weapons guidance and homing, and so on. Automation of select decision-making at the systems level does indeed eliminate some of the uncertainties associated with human decision processes. However, much depends on the intensity of a specific conflict and the extent to which sophisticated weapons and support systems are involved. Still, certain general trends in combat system automation may partially offset and ameliorate (from an analysis standpoint) the increasing complexities of future combat context when it comes to matters of cognition and behavior.

It appears that considerable reconfiguring and restructuring of our military forces will be necessary well into the decades of the next century to keep pace with changes in global conditions. To assist with such tasks, it is only fitting that our military modeling and gaming be forged into the best possible analysis tools to be used in (among other things) the evaluation of force configurations and systems concepts and in establishing force level requirements.

9.4 TOWARD BETTER UNDERSTANDING

This entire paper has been concerned with the portrayal of combat in an analytical light with an ultimate objective of modeling the phenomenon mathematically so that, whether for purposes of development, planning or training, models can be used to measure characteristics of combat outcome. This, in turn, will permit us to gauge the impact on outcome of particular combat variables of interest. The task of properly satisfying this objective is enormously difficult; in the opinion of some, it is impossible. We have here attempted to scope out the dimensions of the task and, in so doing, have basically portrayed the jagged, multipinnacled tip of an iceberg, or perhaps worse yet (but more accurately), the tips of many icebergs. Nonetheless, there are some steps that should move us toward a far better understanding of combat. At the very least, they should give us a clearer picture of what we are incapable of modeling at any time, and why, and furthermore, an appreciation of how such findings may affect the analytical answers that we seek.

We devote the rest of this section to discussing a program of research aimed at exploring some of the major problems already identified. It is not intended as a formal task statement, rather it should serve as an indicator of the depth and sweep of the research that will ultimately be required to satisfy our objectives.

To advance our analytical (and phenomenological) understanding of combat, it is only logical that we begin by validating our candidate combat structure presented in Section 4. Validation must rely on historical accounts of combat, not only to identify the elements of structure defined in this paper but also to make sure they relate to one another as we have postulated. Next, we must trace the performance of functions by the combatant forces, dictated by their respective missions, that interact to create the flow of combat processes defined in Section 4 and Appendix B. These, in turn, can interact to produce a combat outcome.

Corroboration of these phenomena across some reasonable historical spectrum of combat is called for, as is conformance of structure with the writings of classical military theorists and the collective experience of current practitioners in military science (and art). Structural compatibility with projections of future forces and systems, consistent with changing roles and missions, should also be examined. Extensions and modifications should be made as necessary to any of the material discussed in Section 4 and Appendices A and B.

At the heart of combat modeling lies the difficult task of expressing the combat processes in conformance with the defined and validated structure. It is this area that truly calls for extensive analytical and experimental ingenuity both to improve on existing methodologies and to fill important gaps for which few, if any, modeling techniques are currently available. Yet, as often happens, we do not wish to become obsessed with technique for its own sake to the exclusion of the real world of combat that we are trying to emulate.

Our approach to process modeling is, of course, through the event-by-event simulation of combat participants gathering and processing information and making decisions, their manning of weapons, sensors, combat platforms and transport equipment in a realistic physical environment, and their use of suitable tactics and operating doctrine. From this military mélange will emerge patterns of combat results that can be grouped into the processes of Appendix B. Clearly, these areas call for some of the most intensive research effort.

Over and above the mathematical, computational, and man-in-the-loop tools and techniques available to modeling research, however, is our access to various forms of experimentation. Methodology validation, wherever possible, should proceed in parallel with the modeling investigations. Validation options are as discussed in Section 8.5. As noted, it is the cognitive and behavioral aspects of combatants that beg for analytical attention when compared with our existing capabilities to model performance of the hardware elements of weapon and support systems. Using a complete, total description of combat (similar to what has been attempted in this paper), we must first identify existing knowledge gaps and the absence or scarcity of data relative to human performance in combat that frustrate efforts at predictive modeling. A research program designed to overcome these difficulties would involve extraction, where possible, of behavioral data from historical accounts and both psychological and physiological experimentation to measure human performance under controlled conditions representative of combat.

In the broader pursuit of improved process modeling (to include men *and* material), experimentation with simulation and various mathematical programming techniques is clearly called for. Two basic approaches would seem to hold promise; one examining the combat modeling problem from the bottom up (micro-modeling), the other, from the top down (macro-modeling). Also deserving attention, along with research in human performance and combat process modeling, is the question of identifying overall combat issues with those from other known classes of problems in the physical, biological or social sciences. This might show analogous structures and solutions that might provide new perspectives on combat. The assessment would draw on macro-modeling capabilities whereas research efforts in process modeling are oriented more toward micro-modeling.

The micro-modeling, or bottom-up approach can take the form of simulating combatants in situations ranging from one-on-one duels up to force-on-force. In so doing, we can study the increasing complexities of command-control with increasing force levels on the battlefield in addition to learning more about other factors that contribute to combat "friction" (DuBois et al., unpublished manuscript). Also adaptable to this type of investigation are the techniques of cellular automata (Dockery and Woodcock, 1993) that enable us, through math programming with contingency logic, to examine varying tactics, rules of engagement and classes of weaponry on the battlefield. Even recourse to robotics is suggested wherein mobile electromechanical devices (robots) can be constructed with sensors and circuitry endowing the robots with characteristics that parallel certain human emotional and behavioral patterns (such as flight, evasion, hunger, fatigue, and frustration). Such robots, divided into teams and given adversarial objectives, would be turned loose and the resulting behavior noted.

Looking at the combat modeling problem from a macro viewpoint (top-down) affords the investigation of concepts in game theory, control theory, Lanchester theory, catastrophe theory, and chaos theory as to the extent of their applicability to the combat phenomenon (Dockery and Woodcock, 1993). There is also the likelihood that other disciplines and sciences will make further structural and algorithmic contributions to combat models, aided by a macro-modeling approach. Since macro-modeling implies the use of aggregated forces and equipment, the linkages between the low- and high-resolution modeling of combatant units must be clearly and convincingly established.

We have touched on the subject of validation and the fact that it should proceed in parallel with the analytical research. The overall task being outlined here is in itself a vast experiment involved with math programming, simulation, laboratory and field experimentation, scientific and historical research. It consists of investigating and improving combat modeling techniques using certain experimental procedures in a data generation mode while also using variants of such procedures to validate the work done. As demonstrated by Miller (Miller, 1978) and discussed in Section 7.1, there are important self-similarities in the hierarchy of living systems. These may afford us opportunity to select "scenarios" for our investigative work that do not involve combat directly but contain structural elements that parallel those of combat. The scenarios so selected define substitute but similar player objectives that produce effects on player states more or less equivalent to those in combat.

Clearly, this type of effort calls for a high degree of creativity and ingenuity in the design of the overall experiment. However, somewhat in mitigation, is the great flexibility afforded by the universality of combat structure, the self-similarity among combatant units of varying size (Sections 7.1, 7.2), and the alternative top-down and bottom-up views of combat. Furthermore, within the parameters of our overall experiment, we can build simulations (or other models) of selected "surrogate" portions of combat and design validation experiments to match and test these portions in keeping with the concept of "if-then" model constructs (Section 8.3). In this manner, we can start with a piecemeal process that has as its goal the eventual model validation of the entire combat phenomenon.

Briefly, the process would go through the steps of experimental validation of surrogate modeling (noted above), alteration and absorption of surrogate modeling techniques and results into combat submodels, and the careful integration of combat submodels into a "complete" model to be totally or partially validated through concepts of "if=then" combat experimentation. As cumbersome, drawn-out, and complex as the process described may seem, it is likely to represent the only path through the rough, broken terrain of combat modeling that could bring us ever so much closer to predictive modeling.

9.5 ORGANIZING FOR RESEARCH

A few words are in order regarding the kind of research organization and a way of thinking that seems to be needed in undertaking the extensive, complex task outlined above. By spelling out these thoughts, we may also provide added appreciation for the nature and dimensions of the effort being discussed.

To begin with, we are describing an investigation whose duration is more appropriately measured in years than in months. This should not be surprising; the problem of modeling combat within bounds of scientific acceptability has been with us for nearly a half-century, with progress in model improvement being inordinately slow. Much of the progress we have seen has been spurred on by spectacular developments in the computer sciences. Unfortunately, there has been no matching effort focused on the fundamental understanding of combat as a sociotechnological system, the aim of this paper. A system study of this complexity and long duration entails continued interplay among areas of scientific research, experimentation, and math modeling and calls for a broad, multidisciplinary staff of investigators.[13]

Let us consider a wish-list of membership characteristics for a core organization that might successfully undertake the tasks we have outlined. Words come to mind such as knowledgeable, rigorous, patient, motivated, open-minded, objective, curious, creative, imaginative, erudite, collegial, communicative, and articulate. Such a group of investigators should not exceed 10-15 members in order to facilitate communication, information exchange, and to promote continuity and the closest integration of effort. Small group size may conflict with the requirement for wide disciplinary representation, further emphasizing a need for the "renaissance man." Thus, some members would be expected to have expertise across one or more traditional disciplines. We should additionally look for a variety of occupational backgrounds on the research staff to include academia, the uniformed military, government researchers and planners, and scientists from the private sector. This mix will permit us to benefit from differing points of view as we approach and solve problems. Also important are considerations of positive interpersonal dynamics within the group (to the extent that these can be selected or controlled).

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13 Expertise appears to be needed in the fields of mathematics, statistics, physics, engineering, biology, psychology, physiology, military science and operations, computer science, economics, operations research, history, systems science, and experiment design.

In all, three categories of participation seem called for. These are the core group (discussed above), consultants who are called on at appropriate times, and experimental activities/facilities, government and private, that develop empirical data used in model development and validation. Funding support for the effort would be provided by government (Department of Defense) contracts and research grants. It would appear that Service Academies, Armed Forces Universities, and War Colleges would be the most immediate and direct beneficiaries of the work performed, paralleling its application by commands and activities concerned with force planning, contingency planning, doctrine, training and readiness.

It is natural to speculate at this point on some of the practicalities of organizing for the type of investigation being discussed. The dimensions and complexity of the problem are a match for an organization such as the Santa Fe Institute (SFI)[14] except that in this instance we focus on only a single issue: combat. Additionally, the need to conduct and tie in with experiments and military exercises will probably call for a larger, more varied core group staff than is usual at SFI.

The work outlined consists largely of applied research and engineering with clusters of basic and experimental research, to be conducted mostly in connection with aspects of human behavior in combat. This would seem to call for a consortium of representatives from both private and defense institutions of higher learning, government laboratories, federal contract and private sector research organizations. It is difficult to identify a "housekeeping" organization at this juncture, considering the embryonic state of our task outline. However, *continuity* of the effort is of utmost importance along with smooth, rapid communications among the research team members (and with other appropriate activities) of steps taken, progress made, and results obtained. Certainly the rapid advances being made in communications and computer technologies should facilitate such a chore. Nevertheless this would imply a core group more or less fully committed for a period of perhaps several years while planning, coordinating, and executing the work. Experimental activities and research consultants would, of course, cycle into and out of the mainstream effort as dictated by research requirements.

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[14] The Santa Fe Institute (of Santa Fe, NM) is a multidisciplinary graduate research and teaching institution formed to nurture research on complex systems and their simpler elements. Its primary concern is to focus the tools of traditional scientific disciplines and emerging new computer resources on the problems and opportunities that are involved in the multidisciplinary study of complex systems-those fundamental processes that shape almost every aspect of human life.

Finally, most critical to the effort are the leadership qualities called for in whoever assumes responsibilities for direction of this research program. Attributes already touched upon above are most certainly needed in large measure if this monumental research challenge is to be met. We would hope that a clear case has been made for the need to undertake an effort of the scope and dimensions described in this paper.

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APPENDICES

Appendices A and B are presented to provide greater insight into the concept of combat structure advanced in this paper. This material is more closely allied to combat theory than to actual modeling practice. However, models must explicitly or implicitly accommodate the relationships spelled out in the following pages. Appendices A and B have in part been extracted from DuBois et al. (unpublished manuscript). Appendix C is extracted from Low (Low, 1981).

In order to establish a common basis for the development of combat models, it is necessary to develop a taxonomy of combat, and to define terms as exactly as possible, even though the definition may depart from common usage.

APPENDIX A
COMPONENTS OF COMBAT AND A MATTER OF STATE

As an early step in research by The Military Conflict Institute to develop a theory of combat, experienced military opinion was sought through Delphi-like polling techniques as to the factors that most affect the conduct and outcome of combat. This polling produced more than 2,000 such factors. These were classified as components of combat and, when presented in an unstructured and unsorted listing, were not considered to be particularly astonishing or useful. However, after extending the listing from documentary sources and with some intermediate grouping of the material according to parts of speech (nouns, verbs, etc.), all could then be folded into a primitive of combat structure that guided the transformation of the data into elements, attributes, and actions.

Briefly, a combat primitive consists of an element (noun), as modified by attributes (adjectives), acting or operating (verb) on itself or on other elements. The interaction of elements, as described, constitutes an activity that produces results characterized by changes in state for all of the elements involved. State in this context is the condition of existence of an element expressed as a function of time, the element's attributes, and position in space. Terms are defined more formally below.

1. ELEMENTS

Elements are combat components defined to include all entities or things associated with combat. These may be physical or cognitive in nature. As elements, physical entities exist as either animate or inanimate. Animate physical entities include a variety of living beings; the inanimate physical entities include all matter formed in nature and all things that are manmade. Physical elements exist as single entities (e.g., an individual combatant, a tree, a truck) or as collections of the same class (e.g., a battalion, a forest, a motor pool).

Cognitive entities are those that pertain to human feelings and emotions or derive from human intellect and processes of the human mind (e.g., courage, hunger, fatigue, fear, strategy, motivation). Such entities are classified as elements only if they exist beyond and external to some particular animate element of reference (e.g., the national will to fight with reference to an individual combatant). In this example, "national will to fight" is a cognitive element and the "individual combatant" is an animate physical element. Cognitive entities that exist wholly within or internal to an animate element of reference (e.g., individual morale referenced to an individual combatant) are classified as attributes (characteristic performance properties) of that element, as discussed below.

2. ATTRIBUTES

Attributes are combat components defined as the qualitative and quantitative modifiers of combat elements. Attributes are of four kinds, as follows:

(1) Physical properties – Time-dependent descriptors of physical elements only (human and material) that can be stated in precise physical terms (e.g., composition, unit configuration, numbers of units, dimensions, weight, shape, area, volume).

(2) Characteristic performance properties – Technical and behavioral properties of an element that relate to its military functions and the manner in which it performs in combat (e.g., range, ceiling, speed, rate of fire, sense of discipline, vulnerability).

(3) Metrics of performance – Degrees or measures of characteristic performance in a combat context, expressed qualitatively or quantitatively (e.g., high reliability, 0.5 hit probability). This attribute is closely coupled to (2).

(4) Posture – Time-dependent behavioral summaries for human elements in the combat environment (e.g., aggressor, defender, firing, entrenched, advancing, retreating).

The attributes of animate physical elements include all four of the above factors. The attributes of inanimate physical elements consist of (1), (2), and (3) whereas those of cognitive elements consist of (2) and (3) only.

3. STATE

State is the condition of existence of single or collective physical or cognitive elements, expressed as a function of time. State is determined by the appropriate attributes for the element and the element's spatial domain or coordinates.

4. ACTIONS

Actions are combat components defined as acts performed by a single or collective element (as "agent" elements) to change the state of one or more other elements and/or to change its own state (as "object" elements). Examples of such actions are moving, firing, communicating. Most physical action taken by animate elements has intended results that are not always realized because of counter-action by the object elements.

For cognitive elements, "action" is more appropriately expressed by the notion of "influence." A cognitive element (as agent) influences an animate physical element or another cognitive element (as object) to effect changes in the state of the object element with possible attendant changes in agent state. For example, national cultural ideology as a cognitive element influences national will to fight, also a cognitive element. In turn, national will to fight can influence the morale of an individual serviceman. If, in this example, the reference element is the serviceman, then a chain of cognitive elements ultimately has influence on this individual as an animate physical element by way of changing his attributes and hence his state.

Figure A-1 illustrates the relationships among the factors discussed above.

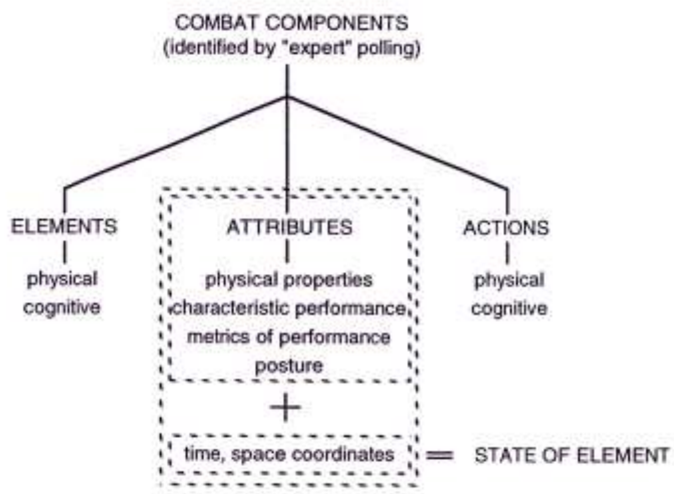

Figure A-1. Combat component categorization

5. ACTIVITIES

An activity is defined by an agent element acting on or influencing an object element. That is, it is defined by the triad "element-action-element." Every such activity triad has a "result" associated with it. Physical and cognitive elements act upon or influence one another in producing the myriad activities associated with combat. Only animate, physical elements can deliberately act to change their own state. Figure A-2 diagrams some types of activity that contribute to combat microstructure.

As a final observation, we note that actions can be aggregated into combat *functions* and activities can be aggregated into combat processes (see Appendix B).

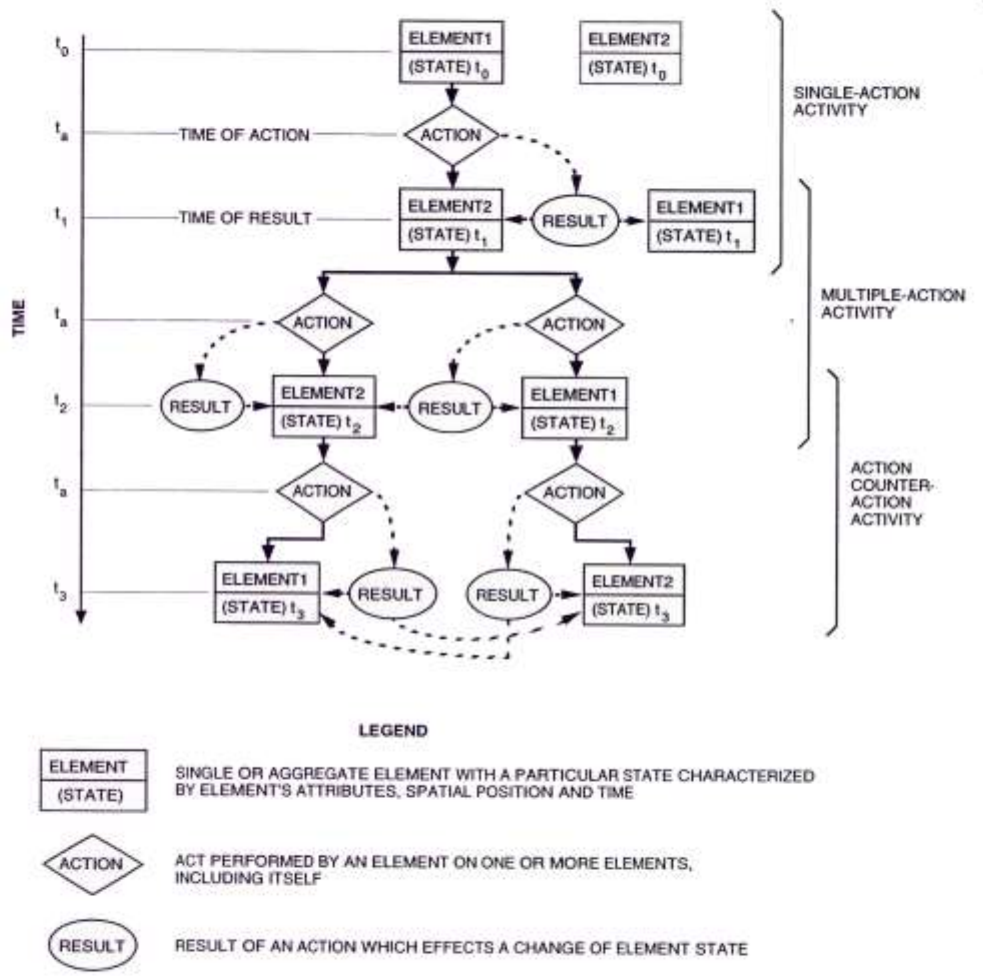

Figure A-2. Combat microstructure of elements, actions, results.

APPENDIX B
PRIMARY COMBAT PROCESSES

We have noted in Section 5 that selection of a set of processes for describing combat (Footnote 4) is a matter of judicious convenience. While there is no theoretical basis for choosing any particular set, the concept of combat process itself is a core principle of the combat theory espoused by The Military Conflict Institute, which underlies the proposed modeling effort. A key point is that this set (or any other set) taken as a whole, is defined as encompassing all combat activity. Thus, as noted in Appendix A, the set represents an aggregation of all activities that occur at element levels.

Processes can be classified as either *externally directed* (primarily impacting enemy forces) or *internally directed* (primarily impacting friendly forces), as shown in Table B-1. Each of these primary combat processes is defined and discussed in this appendix.

Table B-1. PRIMARY COMBAT PROCESSES

Externally Directed Processes (Primarily impact enemy forces)	**Internally Directed Processes** (Primarily impact friendly forces)
Attrition/Destruction	Command-Control
Suppression	Motivation
Demoralization	Information acquisition
Neutralization	Communication
Maneuver	Movement
Disruption	Protection
Deception	Sustainment

EXTERNALLY DIRECTED PROCESSES

Attrition/Destruction

The *attrition1destruction* process applies to both animate and inanimate physical elements, but not to cognitive elements. Destruction includes disablement and damage (partial destruction) as well as complete destruction; attrition represents the cumulative effect of the destruction process over time. Destruction is carried out through the use of a wide range of weaponry, from hand-held weapons to lasers, and including chemical and biological weapons, incendiaries, explosive munitions, and nuclear weapons. Attrition/destruction is the most clearly discernable and the most measurable of all processes in combat, so much so that it is often the only process examined in analyzing combat. Combat environment may be involved in the destruction process, as when men and equipment are lost to severe weather or other environmental hazards and extremes.

2. Suppression

Whereas the attrition/destruction process operates on animate and inanimate elements, the *suppression* process influences only human elements, modifying their attributes (see Appendix A), and thus changing their state. It is primarily the threat of death or injury, leading to fear, that is at work in suppression. But even in the absence of fear of bodily harm, there can be suppression out of concern for preserving the materiel of a unit. The generic result involved in the suppression process is the curtailment of enemy combat activity of any kind that follows from the perception by individuals of danger to them or to other persons or materiel. Suppression is less discernable and measurable than destruction, but is more prevalent on the battlefield and probably has a greater cumulative effect in most combat situations.

Whereas the destruction process leads to physical damage and the loss of elements, the suppression process causes no damage or losses but, acting through mental reactions, it diminishes the amount and efficiency of actions of enemy elements. In so doing, the suppression process directly decreases the opponent's combat effectiveness and it is the extent of the decrease that affords some measure of suppressive efforts.

Whenever the destruction process occurs, the suppression process will usually accompany it. If an infantryman is killed, others observing the death will take cover and their rifle fire will be suppressed. The converse is not true: the suppression process itself never has the result of destroying or damaging.

3. Demoralization

The process of *demoralization* leads to breaking or reducing the will to fight of the opposing force. It operates solely on animate physical elements, with results that range from doubt about the wisdom of continuing to resist to abject loss of will in an entire force. The most pronounced impact occurs when the commander of the enemy force is demoralized, but demoralization can occur from the bottom up within the force, even though the commander and his principal subordinate commanders have not themselves experienced weakening of the will to fight. To some degree, the process affects many combatants in every combat situation. It is when the process affects the command structure or when it becomes truly widespread among the rank and file that the combat power of a force can be catastrophically reduced.

With loss of will, the purpose and values of engaging in combat tend to be discarded in favor of primal impulses to survive, feelings of hopelessness, and desire for psychological palliation. The crucial drive of mission is diminished and, in the extreme, no longer acts to focus combat activity. The effects of the process can be arrested and even reversed during combat by forceful leadership if demoralization has not progressed too far.

The demoralization process is a by-product of other combat processes, most particularly destruction, maneuver, disruption, and deception.

4. Neutralization

The *neutralization* process affects combat through indirect means of negation or denial of the enemy's capability to bring all or a portion of its combat power to bear. Whereas destruction and suppression act to eliminate or diminish the combat power of engaged segments of any enemy force, neutralization acts to totally negate a truly significant fraction of that force, or sometimes the entire force, during the period of neutralization. The process frequently depends on successful use of the maneuver function or the efficacious use of blockade to spatially isolate the neutralized force so that its power cannot be usefully applied. There are other ways to carry out the neutralization process that involve simultaneous processes of deception, disruption, and demoralization as well as the threat of destruction.

The neutralization process resembles the demoralization process, but differs in that the neutralizing cause is something other than loss of will. A force that surrenders because it had lost the will to fight rather than because it was isolated would be counted as having succumbed to demoralization. Surrendering is often, but not necessarily, a consequence of the neutralization process.

5. Maneuver

The *maneuver* process can be thought of as a tactical "end game" of the process of movement; it is primarily intended to gain advantage over the enemy by attaining favorable spatial positioning. Maneuver more generally affords a means of preserving freedom of action to engage in the processes of destruction, suppression, neutralization, disruption, and deception against an enemy and in the protection process with respect to own forces. Maneuver is indeed a two-sided activity that allows for counter-action by an enemy and for environment effects that can be disruptive or supportive. As such, it fits the process definition. However, it clearly works in conjunction with any of several other primary processes, and on occasion, acts as a function.

6. Disruption

The *disruption* process includes activities that interdict the flow of enemy manpower and materiel and activities that disturb and delay enemy processes of command-control, information acquisition, communication, and protection. The disruption process is frequently carried out with the process of destruction, as with the cutting of supply lines and the destruction of enemy transport. Also included are many forms of sabotage to enemy structure, equipment, and manpower. In addition, the disruption process is directly coupled to electronic warfare countermeasures equipment and other means of information warfare that disrupt enemy control, communication, fire direction, and information-gathering activities. This is done through jamming, interference, and usurpation of communication links, sensors, computers, and control systems.

While information warfare plays a significant role in the disruption process, such warfare also carries over into the processes of deception and protection.

7. Deception

The *deception* process reduces enemy combat power by misleading the enemy's information acquisition process, and through this conduit his command-control function. It operates entirely through cognitive entities striking at the central direction systems to be found at all organizational levels. Techniques include directed misinformation, excess or ambiguous information, imitative communications deception, feints, ruses, decoys, fake materiel, camouflage, and the like. Many of these techniques are considered to fall under information warfare and are classified as "soft kill" as opposed to the "hard kill" of the destruction process.

INTERNALLY DIRECTED PROCESSES

8. Command-Control

The *command-control* process directly and strongly affects all combat activities and thus all processes. The process encompasses not only the crucial decision-making and direction that emanates from the command function, but also all forms of control exercised on humans in combat, both from and within an individual, as well as the preprogrammed control routines designed by humans into their weapon systems and equipment. The inclusiveness is such that no action occurs in combat without prior command-control process input except for those actions involving natural phenomena or unforeseen occurrences (acts of chance). The command-control process involves the processing and synthesis of acquired information, including intelligence information, own-force information, and prior knowledge and experience, and the development from this of decisions, directives, orders, estimates, plans, and all other forms of control. There are strong ties between the command-control and the motivation processes.

9. Motivation

The *motivation* process is the converse of the demoralization process operating in the own-force context. Where demoralization has occurred, the motivation process is the restorative, and where demoralization has not yet occurred, motivation is the guard against it. Through this process, a force is infused with the will to fulfill its mission in the face of deadly threats from the enemy. More than that, motivation instills the will to overcome the normal societal mores against inflicting death and destruction on other humans. All internal and external processes further the process of motivation insofar as they are perceived as having favorable outcomes. The motivation process works solely on human elements through modification of their attributes. The degree of motivation (or conversely of demoralization) is crucial.

The primary means for motivation during combat is the command function, supported by control and communication. Motivation is a key responsibility of all in the command chain. This top-down influence is buttressed by peer bonding at all levels, leading to motivation through cohesion. Just as essential are the ingrained motivations that individuals and units carry into battle. These stem from training, national history and culture, and the broader purposes and values attached to the war effort.

10. Information Acquisition

The *information-acquisition* process is concerned with three major areas of information about (1) enemy forces, (2) own forces, and (3) the combat environment. The primary acquisition means are through human sources of sensing and a wide variety of sensor systems and platforms (e.g., radar, sonar, electronic intercept, and magnetic, infrared, seismic, and optical detection). Secondary acquisition means are reports and data in many forms that are collected after information has been communicated from the primary acquisition sources. Information acquisition also encompasses information and data gathered from documents such as policy directives from higher authority, field manuals, standard operating procedures, and computer files.

With regard to own forces, the process includes information communication from higher echelons, and adjacent or nearby forces in addition to that from elements within the force. Information acquisition about the environment includes gathering data on weather, road conditions, railways, airways, rivers, harbors, cross-country trafficability, urban areas, and civil populations. Although acquiring intelligence information is aimed at the enemy, the information is acquired for use internally within the friendly force and therefore the process is classed as internally directed. Acquisition of intelligence will often have an associated direct impact on the enemy, but that impact occurs through one or another of the externally directed processes.

Once acquired and transmitted, intelligence information will be weighed together with own-force information in decision-making by commanders. This mental processing of acquired information and its translation into a knowledge base to be used in deciding subsequent action is part of the command-control process, not the information-acquisition process.

11. Communication

The *communication* process covers all transmissions of information (moving information from one point to another) using any of many means available for the purpose. The means of message transmittal are broadly divided into speech, writing, and telecommunications (in several modes, such as cable, microwave, and fiber-optics). They can also include more primitive means such as smoke signals, light signals, hand signals, and flag signals. Also included in means of transmittal are the lines and nodes governing the routing of telecommunications, along with the establishment of communication procedures and doctrine. Communications security is part of the internally directed process of protection, whereas virtually all of the material transmitted in combat is generated as part of externally and other internally directed processes (most notably, the processes of command-control, information acquisition, and sustainment).

12. Movement

The *movement* process pertains to the longer-range physical transport in three-dimensional space of all elements necessary to carry out combat operations. The range is typically longer than that involved in the maneuver process, where movements are more intricate, but usually remain well within the combat arena. In contrast, the movement process may entail transport over extended lines of communications (LOCs) from staging areas and bases to the area of combat operations and to locations within the combat area itself. Movement and maneuver can be thought of, respectively, as "coarse" and "fine" positioning of resources to carry out a combat mission.

13. Protection

The *protection* process encompasses a broad set of activities that have a common result of protecting the force from the enemy's externally directed processes of destruction, suppression, and disruption, and the enemy's internally directed process of intelligence and information acquisition. The most direct and traditional protection activity is fortifying against enemy firepower. Electronic jamming or encrypting that denies enemy interception of friendly force communications is another protective measure. Jamming that interferes with the enemy's internal communications, however, is a disruption process. Electronic and physical countermeasure activities of many kinds, as well as cover, concealment, camouflage, and dispersion contribute to the process. Protective measures against adverse environmental factors, such as storms, flooding, extreme temperature conditions, and nuclear, chemical, or biological contamination are included.

It is obvious that other processes indirectly help in protecting a force. Destruction, suppression, neutralization, and other externally directed processes indirectly protect by diminishing the enemy combat power that can be brought to bear. The protection process, however, is concerned with the protection afforded by the direct and immediate countering of hostile activities.

14. Sustainment

The *sustainment* process is supportive of all other processes. It is concerned with sustaining all active fighting, support, command-control, and information-acquisition elements. The process embraces the broadest interpretation of what is included in the term "logistics/ support" (Figures 3 and 4 in the main text). It includes both manpower and material support, such as personnel replacements, materiel resupply, medical care, morale, food, fuel, hygiene, transportation, ammunition, repair, maintenance, equipment retrieval, and field engineering.

Sustainment is dispersed throughout many echelons and locations of activity because of the multifunctional capabilities of men and equipment during and between periods of combat.

Figure B-1 is a conceptual illustration of the blending of all combat processes into an overall combat result at time $t + \Delta t$.

FUNCTIONS

Functions are defined as the generic categories of like actions taken by elements of a force in combat. Actions of like kind at a microlevel are gathered together and aggregated with those at higher force levels into primary combat functions for forces of any size. Certain of these functions are performed internally to sustain the operations of the friendly force; others are directed externally, against the enemy. The enemy, in turn, is capable of using appropriate counter functions directed against the opponent functions, internal and external.

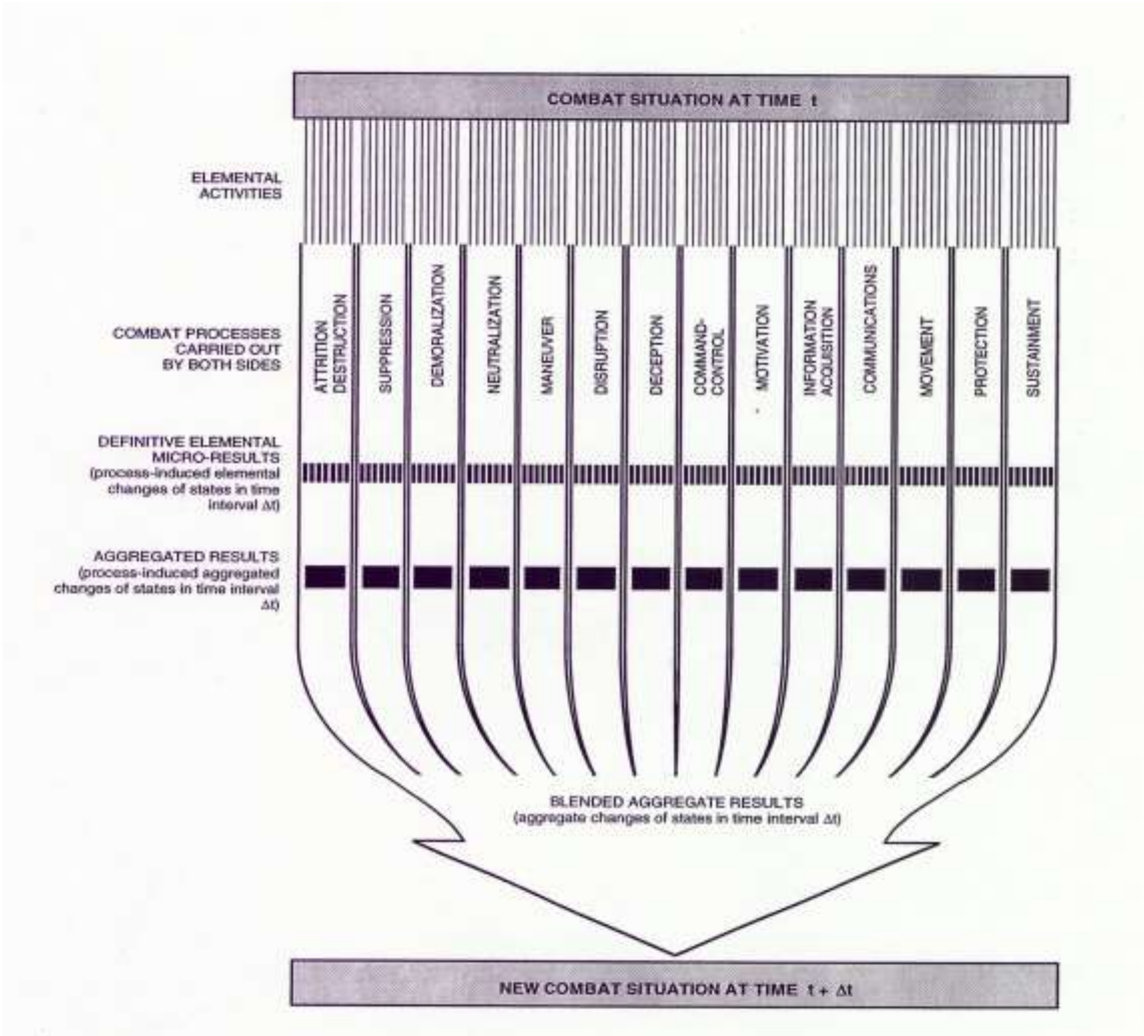

Figure B-1. Blended aggregation of process results

Action is the enabling mechanism for activities, as discussed in Appendix A, and is undertaken by an agent element against an object element with some intended result. This result may or may not be realized from the ensuing activity. There can be many reasons for disparity between intention and outcome. Examples are imperfect execution of agent action, environmental interference with such action, object counter-actions, or conditions of object state not known to the agent. Actual results, on the other hand, develop in part because of the uncertainties and unknowns affecting the opponents, and it is therefore elemental activity that represents the true microcosm of combat. Nevertheless, as the trigger for activity, action and its surrogate term "function" are important in combat structure.

Any list of combat functions will vary from source to source, depending on terminology, specificity, and other factors, but all lists reflecting modern warfare will bear some resemblance. What is important is that, as with processes and activities, a complete list of functions should cover the totality of actions possible in combat. In fact, it could be argued that a list of functions identical to the list of processes shown in Table B-1 might serve quite satisfactorily, provided each of the functions selected was carefully defined. However, since the word "function" and the concept it conveys have long been widely used in the language of military operations, the list of combat functions shown in Table B-2 has been chosen for purposes of this paper. The list is a compendium of terms frequently used to describe functions in service operations manuals. Considerable similarity to the list of processes in Table B-1 can be noted.

Table B-2. PRIMARY COMBAT FUNCTIONS

Command

Control

Communications

Intelligence information acquisition

Own-force information acquisition

Fire

Maneuver

Movement

Electromagnetic actions

Disruption actions

Deception actions

Psychological actions

Cover

Engineering Support

Manpower support

Materiel support

Civil Control

APPENDIX C
EVENT RESULT/TIME PATHS

An illustration of the event-result/time path concept is as follows. In Figure C-1, Blue is fighting Red in a highly stylized combat situation. B_o and R_o are the total resources for Blue and Red, respectively, at the start of the campaign, ß and ρ are the surviving resources at the end of the campaign. It is further assumed that the campaign ends before the survivors of the losing side are reduced to zero. If we define $ß_c$ and ρ_c as the minimum levels of resources with which Blue and Red, respectively, can continue to fight, the campaign ends when $ß = ß_c$ (in which case $\rho \geq \rho_c$) or when $\rho = \rho_c$ (in which case $ß \geq ß_c$).

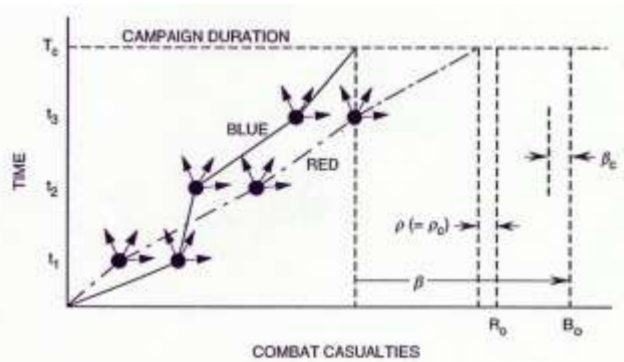

Figure C-1. Example of event-result (casualty)/time parts

Major decisions on the commitment and employment of resources are made by Blue and Red commanders at times t_1, t_2, t_3, ... t_c. The small arrows at these points in time along the Blue and Red casualty-time paths reflect the fact that many alternative decisions could be made by both sides. Decisions differing from those shown would result in new casualty/time paths of Blue and Red. If we define (ß-ρ) as a possible measure of the campaign outcome, it can readily be seen that different decisions, leading to different "paths," would result in different ß's and ρ's and, hence, different outcomes. Running one exercise or one manual war game identifies only one decision/event path out of a virtually infinite number of possible paths.