Game Theory for the Maritime Professional

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Abstract: *Whether engaged in design, construction, maintenance or operations activities, Naval Architects and Marine Engineers are continually engaged in negotiation and decision making. However, very little formal negotiation and decision making training exists for NAMEs, despite the fact that in recent decades there have been significant developments in the game theory field. These developments in game theory have resulted in a standardized terminology and provide theoretical and mathematical concepts that, when adopted in the maritime community, could provide significant advantages to the initiated professional. This paper provides introductions to game theory concepts that have immediate application to typical activities that NAMEs are engaged in on a day-to-day basis.*

Application of these concepts can result in better and more rapid decision making and assists in the disentanglement of technical and operational problems when they occur. Understanding of these concepts can be as vital as oral and written communication skills for engineers to successfully achieve their technical objectives for the client's and the public's best interests.

This paper presents these concepts at an introductory level and provides several maritime examples, but also provides a substantial amount of references and a bibliography for further study.

Game theory concepts discussed in this paper include the Prisoner's Dilemma, Tit for Tat, the Nash equilibrium, BATNA, Pareto optimality, and the OODA loop.

1. INTRODUCTION

Game theory is the branch of applied sciences involved with the effort to mathematically formalize strategic decision making. Game theory describes various types of interactions between multiple parties through the use of quantified losses and gains dependent on the actions taken by each party. Optimization routines can then be used to maximize gains for an individual or the collective parties in order to assist with complex decision making. Game theory is often simply referred to as "strategic thinking." Game theory as it exists within the applied mathematics field is a relatively new phenomenon and has been applied most rigorously in economics, business, warfare, political science, and more recently in biology and engineering.

Of course, many game theory concepts are as old as decision making itself. Game theory discussions have occurred throughout written literature, often in the context of religion[1]. Game theory discussions have also shown up in design and naval architecture and marine engineering and have been specifically described for naval vessel design. One famous example is the design of the first US frigates, where, given the fact that the US Navy would never be able to win a fleet action, a decision was made to focus on single vessel combat where the US frigates could outfight equivalent opposing frigates but run from larger vessels or fleets of vessels.

More recently (really only since WWII) game theory has developed a mathematical language that allows more formal analysis of, and experimentation with, game settings. This approach marks a more rational analysis of game settings, which is inherently attractive to the engineering field.

Engineers have the reputation of being "rational" thinkers and often support this notion with mathematical and physical analysis, but at the undergraduate and non specialized engineering level, game theory is rarely addressed. Therefore, without game theory analysis, engineers may develop physically correct solutions for decision making internally based on experience (sometimes referred to as "intuition"[2]) but still not attain the ultimate goal of truly solving the problem.

This is a shame, since game theory is easily explained to engineers and a relatively small amount of game theory can go a long way in obtaining an advantage over other interests, be they uninitiated engineers, non-engineers or the inherent complexity of the projects that engineers engage in.

Game theory may be useful in the following maritime pursuits:

- Negotiations
- Optimizations (in finance and design)
- Establishing cooperation
- Rapid decision making
- Competition
- Commerce
- Warfare

We will discuss maritime versions of these pursuits in this paper and relate them to various game theory concepts. It is interesting to discuss maritime concepts in game theory since many quite ancient practical maritime solution approaches can be shown to rely on more modern game theory concepts. In other words, many years ago participants in the maritime field developed solutions on a "gut check" level that only today can be formally and mathematically described.

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[1] "Pascal's Wager" is an example of religious game theory. See Section 233 of *Pensees* by Blaise Pascal.
[2] See the discussion of "intuition" in Klein's *Sources of Power*.

Study of game theory concepts allows more rapid dissemination of refined solutions than "gut check" approaches based on years of trial and error experience.

2. SCOPE

Game theory mathematical formulations have been developed for a wide variety of scenarios to date, but (as with any new field) there are still many interactions not yet described[3]. Useful formulations have been developed for interactions including zero-sum games (directly adversarial scenarios between players, where a gain from one player has a 1:1 ratio with a loss from another player) and non-zero-sum games (particularly in scenarios that would not normally result in mutual cooperation), finitely and infinitely repeated games (which distinguish between single interactions and games where players interact on multiple occasions over time), and more recently asymmetric information games (where some players are aware of information that others are not).

We have limited the scope to two (and occasionally three) player interactions. We have also chosen to not discuss zero-sum games. While zero-sum games were among the first scenarios described by formal game theory, they are most applicable in actual "games" (e.g. chess) and are only very rarely found in trade (and therefore, maritime) interactions, where cooperation often yields greater collective payoffs.

We will discuss a number of non-zero-sum game types, describe how the optimal decision may change in the case of finitely versus infinitely repeated games, and occasionally discuss asymmetric information. While we outline the mathematical representations wherever possible, we have attempted to make the paper readable for the general working engineer and make reference to more detailed mathematical formulation where we feel the mathematical discussion would be too unwieldy or take too much time for an engineer previously unfamiliar with game theory.

3. UTILITY THEORY

Before we begin our more detailed discussion of game theory, it is necessary to introduce the concept of "utility". In fact, the mathematical formalization of game theory was really made possible by the development of utility theory. Utility is a unit used widely in economics to describe preferences between goods (like consumer products), as well as the marginal preferences between varying amounts of a good. Utility may also simply be described as the happiness or satisfaction one achieves from a unit of a particular good.

More of a good would appear to be better, but this assumption is dispelled with the classic doughnut consumption example used in ECON 101 classes all over the world. Feed a freshman a doughnut and ask him how much he enjoyed it on a scale of 1-10. Repeat as needed. A sufficiently cruel professor will eventually drive the student to negative marginal utilities. Negative marginal utilities are rarely realized in monetary

[3] Particularly challenging is the fact that the complexity of game theory formulations tends to increase by many orders of magnitude as additional players are added to the game. Therefore, the most developed games to date are two-player games.

scenarios, since everyone enjoys an extra dollar. However, it is normally assumed that the marginal utility of a dollar decreases as you receive more money. Therefore, a dollar is worth more to a poor man than a rich man. It would also follow that you would care more about going from $0 to $1, than $1,000,000 to $1,000,001. Research indicates that almost all people display utility functions that are risk-averse and therefore concave (e.g. u(x)=log(x), which gradually becomes more horizontal).

Using underlying utility functions, the payoffs of various players in game theory scenarios could be more accurately defined. For example, in a shipyard negotiation scenario, this allows payoffs to be defined not simply in monetary terms, but in terms of utility as a function of money. We might expect in a shipyard negotiation scenario that one party would value a certain amount of money differently than the other negotiating party. For example, imagine that Shipyard A has a risk-neutral (i.e. linear) utility curve[4], but that Client B has a modified risk-neutral utility curve, as shown in Figure 1.

There are a variety of reasons that Client B's utility curve might be modified from the standard risk-averse utility curve, but perhaps in this scenario he was told by his boss to negotiate down the cost of the job by $50,000 – therefore, he has a much steeper utility curve before $50,000 in savings than after. Note that it would still be nice to go back to his boss with savings greater than $50,000, so the slope of the utility curve is still positive after $50,000.

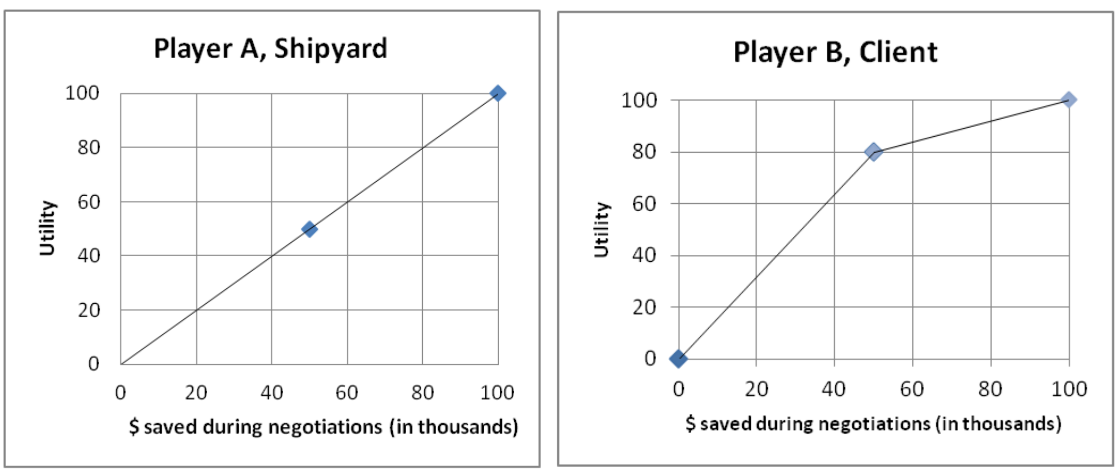

Figure 1. Utility curves for shipyard negotiation scenario

The important point in this discussion is to remember that for each payoff scheme described in this paper, there is actually an underlying utility function that describes the player's payoffs. This becomes especially important when a decision made by a player

[4] Note that this contradicts our previous paragraph, where we suggest that players tend to have risk-averse (concave) utility functions. We have used a linear utility function in this example both for ease of demonstration, and due to the lead author's theory regarding the *Dutch utility curve* ("A Dutch shipyard cares just as much about the 1,000,001th dollar as he does about the first dollar." This is also expressed by the lead author's father-in-law as: "The trouble with the Dutch is giving too little and asking too much.")

will result in a probability of a certain outcome, rather than a known outcome[5]. If opposing player's utility curves are not known this becomes asymmetric information and can result in negotiation confusions.

We will not discuss utility curves in any more detail in this paper since it rapidly becomes complex and is not important for the practical use of game theory on an introductory level, except to remember that the payoffs must be represented in terms of utility. However, if one wishes to study the mathematics of game theory in more depth, a solid grasp of utility theory is imperative.

4. PRISONER'S DILEMMA

We will begin our discussion of game theory concepts with one of the most famous, and one of the most useful, non-zero-sum games: the Prisoner's Dilemma. The concept was originally mathematically developed by mathematicians Merrill Flood and Melvin Dresher in 1950, and later formalized and given its context and name by mathematician Albert W. Tucker[6].

Prisoner's Dilemma is an example of how two parties may not work in their collective best interests by assessing only their own payoff options. There are various versions of the game, but it essentially works as follows:

> *Suppose that two members of a criminal gang are arrested and imprisoned. Each prisoner is in solitary confinement. The police admit they don't have enough evidence to convict the pair on the principal charge. They plan to sentence both to a year in prison on a lesser charge. Simultaneously, the police offer each prisoner a Faustian bargain. Each prisoner is given the opportunity either to betray the other, by testifying that the other committed the crime, or to cooperate with the other by remaining silent. If the prisoner betrays the other he will go free but the other will receive a longer sentence. If they both betray each other they will both receive an intermediate sentence.*

In our example, let's assume that payoffs are as follows:

	A betrays	A remains silent
B betrays	(-2, -2)	(-3, 0)
B remains silent	(0, -3)	(-1, -1)

Table 1. Basic Prisoner's Dilemma payoff table

where notation is (Player A payoff, Player B payoff). Note that the payoffs in this case are actually negative, since the payoff is measured in prison time[7]. So if we look at the

[5] For more on this, examine von Neumann-Morgenstern utility functions, and the resulting Expected Utility Theorem I.

[6] The mathematical solution to the Prisoner's Dilemma is still ongoing, as shown by the recent discovery by William Press and Freeman Dyson of the Princeton Institute of Advanced Studies. See the annotated bibliography.

[7] Note that technically, the payoffs should be represented in amounts of utility as a function of years in prison. Using this methodology, a more powerful mathematical representation can be developed.

intersection of A betrays and B remains silent, the payoff is (0, -3) which means A walks and B gets three years in prison.

It is noted that Prisoner's Dilemma is not a zero-sum game, and therefore that there are scenarios which may be more or less desirable for the *collective* set of players. These may simply be represented as the sum of the payoffs of all players in a particular scenario.

It is evident in this payoff structure that it is in the *collective* best interest of the parties to both remain silent (payoff (-1,-1)), resulting in a collective total of 2 years prison time. However, each individual would be happier betraying their partner if the other remains silent, thereby avoiding prison time altogether. If both players use this strategy, the result will be the payoff in the upper left corner, which has the worst collective payoff of (-4).

Also noteworthy is that payoffs may vary. If silence by both prisoners results in release of both prisoners, one can readily discern that the decision making motivations will change. However, while payoffs may vary, it only remains a true Prisoner's Dilemma game as long the following two key characteristics for a Player i facing Player -i are met:

$$(N_{i*},C_{-i}) > (C_i,C_{-i}) > (N_i,N_{-i}) > (C_i,N_{-i}) \qquad \text{(Equation 1)}$$

$$(C_i, C_{-i}) > \frac{[(N_{i*},C_{-i}) + (C_i,N_{-i})]}{2} \qquad \text{(Equation 2)}$$

Where: C = payoff if Player cooperates[8]
N = payoff if Player does not cooperate
Subscripts denote Player
* denotes a dominant strategy

Note that each player has what is called a *dominant strategy*[9]. A dominant strategy exists when a player has a decision which is preferable or equal to another decision regardless of what the other player decides. In this case, if B stays silent (denoted as "C" in Equations 1 and 2), the payoff for A to betray (denoted as "N" in Equations 1 and 2) is higher (0 vs. -1). If B betrays ("N"), the payoff for A to betray ("N") is also higher (-2 vs. -3). If we assume that Player A is rational[10], A will choose to betray, since A gets a higher payoff for betraying regardless of what B chooses. The scenario is the same for Player B. Therefore, the game will conclude with both players betraying – a less desirable situation than both remaining silent!

The Prisoner's Dilemma is often used as an exercise by mathematicians and game theorists to develop strategies which lead the individual players to make decisions

[8] Cooperation means cooperation between players (not to be confused with cooperation with the police).
[9] Technically, this scenario is termed a "strictly dominant strategy". The Prisoner's Dilemma scenario in Table 3 is an example of a "weakly dominant strategy", since the payoffs are equal (i.e. not strictly better) to the other option in the case of betrayal (in either case the player will receive 0 payoff).
[10] A "rational" player is usually defined in economics as a "utility maximizer", meaning that a player will make a decision in his or her own best interests. This includes any utility he may gain from the other player's happiness, as in marriage partners' utility curves.

moving towards the bottom right corner of Table 1 – i.e. towards cooperation in the players' collective best interests. But that includes a learning or training (or even evolutionary) approach and therefore, by nature, it would indicate the use of multiple rounds of the Prisoner's Dilemma (in other words, the study of hardened "criminals"). This is described as the Iterative Prisoner's Dilemma and study of this form of the Prisoner's Dilemma resulted in useful insights.

4.1 Iterative Prisoner's Dilemma

In an isolated iteration (single round) of Prisoner's Dilemma, both players will choose their dominant strategy, resulting in non-cooperation, unless there is some kind of intervention. This is inherent in the structure of Prisoner's Dilemma, even with modified payoffs, because of the rules established in Equations (1) and (2).

An extension of Prisoner's Dilemma which may result in cooperation is multiple rounds of the game with the same individuals. In this case, we can expect that players might decide to place some trust in their partner in order to maintain cooperation from them in the next iteration. Players could then secure a constant stream of (-1,-1) payoffs through time and maximize their utility.[11]

However, cooperation into the future requires trust between the players, and is therefore fundamentally based on data[12]. Much of this data is experience-based: How well do I know my partner-in-crime? What have my past interactions with him taught me about his future actions?

In the iterative approach, the specific payoff structure also affects decision making (within the constraints outlined in Equations 1 and 2)[13]. For example, let's assume instead of Table 1 payoffs, that the payoff structure looks like Table 2 below.

	A betrays	A remains silent
B betrays	(-5, -5)	(-10, 0)
B remains silent	(0, -10)	(-4, -4)

Table 2. Modified Prisoner's Dilemma payoff table

While it is still *collectively* in the best interest of the parties to remain silent, this payoff structure requires more trust between players, since being betrayed represents a higher cost, and the benefits of mutual cooperation (both in real terms and as compared to mutual betrayal) are lower.

[11] This is why the Mafia developed the concept of "Omerta": the Code of Silence.
[12] Data is incredibly important in game theory. Data can be hidden or shared, correct or incorrect, symmetric and asymmetric and each type has an effect on game analysis.
[13] Note that one further aspect of the Iterative Prisoner's Dilemma that affects player decisions is the amount that future payoffs will be discounted, i.e. the economic discount rate w. See Axelrod's *Evolution of Cooperation* for further discussions of the effects of different values of w.

Let's also examine the possibility that the police have no lesser charge to pin on the prisoners in the case that neither defect. In this case, the payoff structure may look like:

	A betrays	A remains silent
B betrays	(-3, -3)	(-5, 0)
B remains silent	(0, -5)	(0, 0)

Table 3. Modified Prisoner's Dilemma payoff table, with weakly dominant strategies

If the players are established partners-in-crime and trust each other completely, the Table 3 payoff structure would most almost automatically result in cooperation. In this way, prisoners that know and trust each other will avoid prison time completely (although apparently they aren't clever enough to avoid getting dragged into the police station over and over).

Despite the continued reference to criminals, the Prisoner's Dilemma decision making pattern just as easily relates to legal activities such as negotiation, social cooperation and sales scenarios.

The study of Iterative Prisoner's Dilemmas showed that players could benefit from developing strategies that respond to historical choices of opposing players[14] instead of simply having to make isolated choices, which leads us to Tit for Tat.

5. TIT FOR TAT

In the 1980s, the advent of micro-computers allowed aficionados to play out two-player iterated Prisoner's Dilemma scenarios with a population of many players and identify effective strategies for multiple rounds. The most famous competition was the Axelrod Tournament, hosted by a University of Michigan political science professor named Robert Axelrod.

Axelrod invited various game theorists to submit computer programs with pre-determined strategies. Each strategy was allowed to consider the actions of the other player in previous interactions, so a game theorist could design the strategy to respond to another player's actions and therefore become more sophisticated than just a strategy such as "always cooperate" or "cooperate 50% of the time". These strategies could play against each other and it would be possible to score each strategy on the cumulative payoffs acquired in multiple rounds. Axelrod then developed a computer program that, for each subsequent round, populated the player field with more high scoring strategies and gradually eliminated the less successful strategies. The winner of that Axelrod Tournament was the strategy that became dominant in the population after a large number of rounds[15].

[14] In an attempt to predict future opposing player choices.
[15] The actual story of the development of the Axelrod Tournament is much longer and more nuanced. See *The Evolution of Cooperation* in the bibliography.

While Axelrod expected a complex program to win, the "winner" of the Axelrod Tournament was actually found to be a simple strategy called Tit-for-Tat submitted by Anatol Rapoport. In Tit-for-Tat, the player will always cooperate on the first iteration. In the second and all subsequent iterations, the player will mimic the other player's previous choice[16]; i.e. if the other player chooses to cooperate in Round 1, the Tit-for-Tat player will cooperate in Round 2, but if the player chooses non-cooperation in Round 1, the Tit-for-Tat player will not cooperate in Round 2.

Note that "winner" is in quotations – this is related to the fact that the Tit-for-Tat strategy failed to populate the entire game. Instead, it was found that multiple-player iterated prisoner's dilemma games tends to develop an equilibrium with a majority of cooperators (mostly Tit-for-Tat type strategies) and a small minority of non-cooperators.

This makes sense, since a number of non-cooperator strategies will survive by winning against a large population of Tit-for-Tat strategies through betrayal in the first round, but the non-cooperator population is limited by interactions of non-cooperators with other non-cooperators, with results in the "upper left hand" scenario of Tables 1-3, and low associated payoffs.

This equilibrium can also be found in the real world at many levels. In nature, the same concept applies, and game theory has actually been used to show the evolution of cooperation in nature and the game dynamics of viruses and parasites[17]. In human society, we might call the non-cooperators freeloaders, or just jerks.

This begs the question of how we might successfully reduce or eliminate non-cooperators. In maritime, a very successful example of reducing non-cooperators has emerged, which is known as the Joint Survey[18].

> *When there is a finding or a potential dispute in maritime commerce, the evidence (data) may be on a high value moving object (a ship) and therefore cannot be easily or economically stored for later examination. In order to reduce potential conflict and confusion in maritime, there is a long standing tradition of joint examination of evidence to allow commerce to continue to proceed with as little interruption as possible. During joint surveys, representatives of all parties at interest (still described legally today as "participants in the adventure") jointly examine the evidence and formulate a joint written agreement called a "Field Survey Report" that describes the nature, cause, extent and recommended repairs of damages or conditions noted. Upon completion of the*

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[16] Note that this means that if Player B decides to not cooperate on Round 3 but cooperate again on Round 4, Player A (a Tit-for-Tatter) will punish Player B by not cooperating on Round 4 but will forgive the player immediately upon their cooperation in Round 4 by cooperating again in Round 5. Other varieties of Tit-for-Tat have more or less forgiving policies. "Tit-for-Two-Tats" is a more forgiving strategy where Player A only betrays after Player B betrays twice. Conversely, a "trigger" strategy starts off cooperating, but will never cooperate again after a betrayal. See Axelrod's *The Evolution of Cooperation* for other Prisoner's Dilemma strategies.

[17] See Chapter 5 of Axelrod's *The Evolution of Cooperation* and many later studies and publications in the biology community.

[18] For a more detailed description of the joint survey, see the paper "The Joint Field Survey Process: Multi Party Joint Forensic Engineering Investigations in Litigation and Mediation/Arbitration" by Rik van Hemmen, June 2000, Volume XVII No. 1 issue of the Journal of the National Academy of Forensic Engineers (text also available on www.martinottaway.com)

survey all representatives of the parties will sign the field survey and this survey becomes a powerful binding document. The report specifically does not speculate on contractual issues (as such it is signed: "without prejudice to policy conditions or legal interpretations"), but as completely as possible describes the technical facts up to the cost of repairs and may sometimes even describe technical causes.

Joint field surveys work extremely effectively in maritime cultures where the concept is well established, but when a new player enters the field (an inexperienced surveyor, or a surveyor who does not expect to have to continue to play in that particular field) that surveyor may chose not to sign for any number, but generally "selfish", reasons. An incompletely signed field survey still has value, but much less value than a survey that is signed by all parties at interest.

If we examine the Joint Survey, it may actually be described as another version of the Prisoner's Dilemma extended to more than two players, where the payoff structures may look like the diagrams provided in Figures 2a and 2b[19].

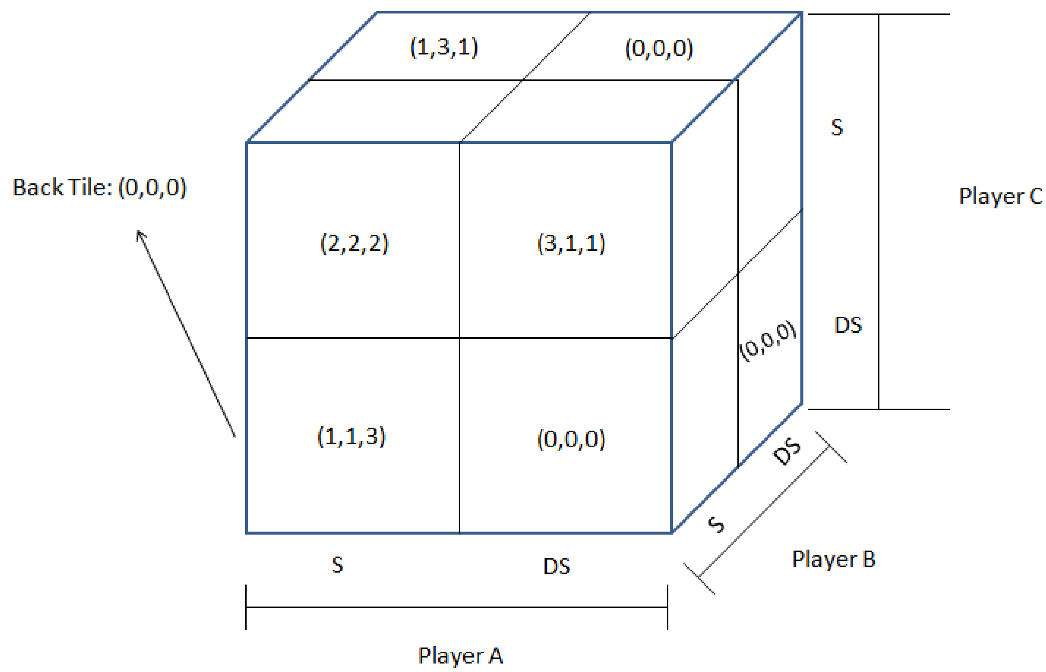

Figure 2a. Three player Joint Survey Prisoner's Dilemma payoff table, strategic form. S = Sign, DS = Does not Sign

[19] Note that the payoff structures are the same in 2a and 2b. The diagrams just illustrate the difference between the "strategic form" and "extensive form" of displaying payoffs. For a discussion of the two types, see Chapter 2 of Dutta's textbook "Strategies and Games"

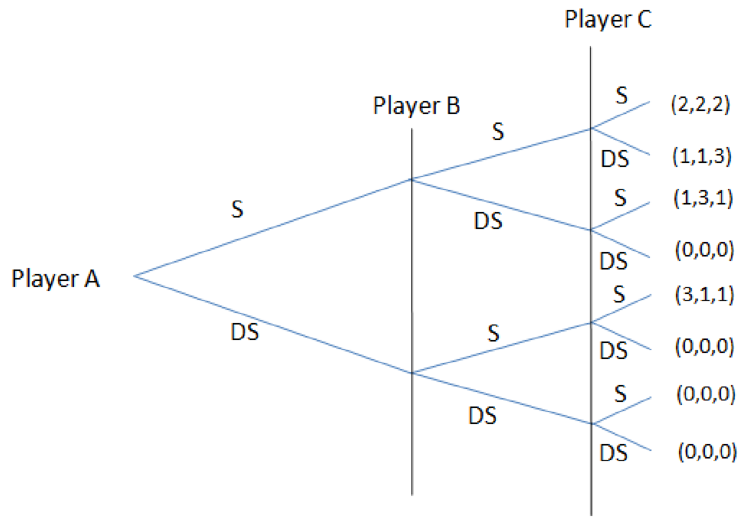

Figure 2b. Three player Joint Survey Prisoner's Dilemma payoff table, extensive form. S = Sign, DS = Does not sign

As shown in the diagrams, a single player may benefit by not signing the Joint Survey while all other parties do. In this way, he may avoid locking down the facts of the matter to maintain later deniability, but still allows the other parties to be locked in. However, if all parties do not cooperate (i.e. do not sign), no facts are agreed upon and the case rapidly becomes messier, when everyone returns to their cubicles with different perceptions of the facts, and by extension, the case becomes more costly overall.

The results of Axelrod Tournaments, and other computer programs, have shown that in general (depending on the cooperator strategies and payoff structure) the percentage of non-cooperators at equilibrium hovers at around 10%. However, practicing surveyors in stable marine communities know that the percentage of non-cooperators in the Joint Survey structure is actually lower than that.

An assumption of the Axelrod tournament is that players do not see interactions they are not directly involved with. This is often the case in reality, but may be decreased by increasing transparency, and therefore allowing outsiders to view the actions of other players. This forces the players to consider the possibility of future interactions of other players in their payoff structure, and incentivizes cooperation.

This is also the reason that the Joint Survey process has a lower percentage of non-cooperators. The Joint Survey is a very transparent process, since the marine surveying community is small and interconnected, even though it is global.

Note that the Joint Field Survey process can only be successful if there are many examples of successful Field Surveys, and this level of cooperation also requires persistence and discipline. Therefore, preparing a quick and simple Field Survey Report on a less contentious issue is as significant as preparing a Field Survey Report on a contentious issue. The confidence and transparency developed in the less contentious reports provides the momentum to handle the more contentious situations[20].

5.1 The Hanseatic League

Based on the results of his tournaments, Axelrod developed four main suggestions for individual choice within the context of an Iterated Prisoner's Dilemma scenario:

1. Do not be the first to defect (be nice)
2. Reciprocate both cooperation and defection (be retaliatory)
3. Do not be too clever (be predictable)
4. Do not be envious of the other player's success (be gracious)

We can see Axelrod's principles in many maritime applications, and as a classic maritime example, one can examine the dynamics of the Hanseatic League[21].

During the dark ages long range maritime trade collapsed in Europe. The emergence from the dark ages first occurred in Italy, most notably in Venice and in a somewhat different manner in Northern Europe in the form of long range maritime trade. The emergence of long range maritime trade in Northern Europe was represented by the Hanseatic League, and its development was similar to an iterated prisoner's dilemma supported by Tit-for-Tat and new concepts of transparency. The Venetian renaissance was mostly obtained by naval hegemony (but supported by the transparency of double entry book keeping), but in northern Europe smaller and non-dominant port cities that were only marginally controlled by inland royalty started developing trading relationships with ports that could offer goods that were of mutual benefit.

One driving trade was the supply of salt to fishing towns for fish preservation purposes. While trade appears to be a seamless process today, it is far from certain that taking one's vessel into a strange port will result in mutually fruitful trade and instead could result in simple confiscation of one's vessel and loss of personal liberty. However, ports (led by Lubeck) started developing these levels of mutual trust and communication (probably based on the high mutual benefits for sale and purchase of salt) and soon required banking and brokerage services. Banking and brokerage especially are pure good faith services and these relatively small scale efforts provided tremendous mutual benefits in these relatively small population centers. This trade resulted in a compact that is generally described as the Hanseatic League, and the League developed rules. These rules varied over the years but applied to banking and credit arrangements, mutual defense and free trade agreements.

In essence the Hanseatic League employed Tit-for-Tat rules, and since the benefit of joining was high (fabulous wealth for the trader middle class) and the penalty for

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[20] This can be mathematically expressed, but we have not encountered a mathematical treatment of the Iterated Prisoner's Dilemma that contains these variables.
[21] As another example, one can consider fishing or whaling regulations, and the development of multi-nation cooperative mechanisms.

defecting was high (generally boycott from the trade system until cooperation was re-established), the system showed remarkable stability over a number of centuries even though the individual players remained independent and the cities were small as compared to the land and populations in the hinterlands. The Hanseatic League failed in the 1700's not because the concept became invalid, but rather due to the development of nation states in Northern Europe that could dominate specific portions of the league (think "Divide and Conquer").

5.2 Miscommunications in Tit-for-Tat

While Tit-for-Tat is the winning strategy for most Prisoner's Dilemma computer programs, some have theorized that this is not actually the ideal strategy for human interaction, which is subject to mistakes. For example, imagine that both Player A and Player B use the Tit-for-Tat strategy. Then imagine that Player A misreads the situation and is given the impression that Player B has betrayed on any particular round. Player B will then betray on the following round, and all future interactions will result in the undesirable "upper left hand" scenario of non-cooperation.

In this case, it may be better to adopt a Tit-for-Two-Tats ("Generous Tit-for-Tat") strategy, where a single betrayal is forgiven as a possible mistake, but two betrayals results in the non-cooperation on the next round[22].

Generosity cannot always be provided in human settings, and while turning the other cheek may be effective in areas where truth is fuzzy, in engineering Tit for Two Tats is often unnecessary.

Let us consider a maritime application:

> *Suppose that two surveyors are attending on a damaged barge in a precarious stability situation where sighting possible damage to internals is required. There is a single very long ladder leading to a hatch where the internals may be sighted. The underwriter's surveyor (who is young and light) climbs the ladder to view the damage and announces that the internals are not affected. Meanwhile the much larger Owner's surveyor who has held the ladder in place has to decide: Should the Owner's surveyor also climb the ladder to ensure there are no damages, or will he trust the initial assessment?*

This is a complex issue and, again related to payoffs and Prisoner's Dilemma strategies.

In maritime there are surveyors that pass the ladder test and others that do not. Those that do not, have failed only once, but face a tremendous burden in regaining that trust in the relatively small and open marine community. Other surveyors will probably not apply a Tit-for-Two-Tats strategy to a surveyor that fails the ladder test but rather will use a Two-

[22] There is suspicion that Tit-for-Two-Tats is actually a more effective strategy in a board populated with innocent players. This has been investigated by computer programs which incorporate a certain level of "noise" representing miscommunications. See Nowak and Sigmund's "Tit for Tat in heterogeneous populations", 1992, *Nature*.

Tits-for-Tat strategy, or even a Trigger strategy (unlimited defections following a betrayal).

As another example, marine insurance is a collection of many Prisoner's Dilemma interactions, since it benefits from mutual cooperation, but an individual party may benefit by betraying. The principle of "utmost good faith" is a legal concept used in insurance contracts which obligates parties to provide all information which might influence the other parties' decisions in the matter.

Utmost good faith is a concept used widely in insurance contracts today, but was first introduced in the maritime world many years ago. It is a concept in international maritime law that requires an insured to deal at a level of truthfulness that is unusual in the land based world. This rule was developed because it is inherently very difficult to verify truth in commerce where the insured object can be very far removed from the insurance company. As such, the law, underwriters, and ship owners agree that total truth is essential and very heavily punish ship owners when even small untruths[23] are discovered by total claim denial and possible expulsion from the entire maritime adventure (this is actually represented as a Trigger strategy).

Conversely, marine underwriters also contribute a level of good faith in claims acceptance that is often described as: "If it could have reasonably happened that way then we will accept that it happened that way." In other words, marine underwriters normally do not investigate the cause of a claim any further than to obtain a reasonable level of assurance that the damage was covered and will almost always accept the most likely cause of the damage rather than argue that it could also have been caused by a less likely event.

5.3 Lloyd's Open Form

The ladder test does not exist in certain maritime situations mostly because no prior data about the other players is available. There are various ways to deal with such an obstacle to cooperation. Insurance insists upon utmost good faith (assume the best), but Lloyd's Open Form (LOF) uses a different approach (i.e. "I am not going to bother to even predict the trustworthiness of the other player").

> *Suppose that a ship is in trouble and needs help. A tug arrives to provide help, but the ship has no idea whether this professed helper is reliable or not. The ship would like to accept any type of help – the question is on which terms. Establishing terms requires negotiations with a rapidly changing position along the steep portion of the ship's utility curve (the ship is flooding, there is equipment or cargo damage, there is oil in water, etc).*

The marine industry developed a procedure that shortcuts the negotiation process at the time of the emergency, which is represented by Lloyd's Open Form. LOF does not

[23] In land based law various levels of untruth are allowed. These untruths are called puffs and are allowed to be used in sales pitches. Maritime law generally does not get involved in such prevarications. Note how lack of tolerance for untruths is a Tit-for-Tat approach, and how tolerance for untruth can result in reduced cooperative efficiencies (increased percentage of non-cooperators).

engage in negotiations at the time salvage is offered. Instead, it states “I will accept your offer of help, but I will not pay if you are not successful. On the other hand, if you are successful, I will pay reasonable fees and an additional reward that will be judged in arbitration after your efforts have been proven to be successful.”

In effect, this approach substitutes a mutually known process (LOF) in a situation where no further knowledge (data) is available.

Interestingly, while the actual players (ship and local tug) have no measure of faith or knowledge about each other, the follow-up players (salvage companies and Owners/ underwriters as an industry) do have the benefit of prior knowledge, having used the LOF arbitration process many times. Only if these arbitrations consistently provide reasonable rewards, will salvage companies be willing to engage in salvage work under LOF[24].

6. PARETO OPTIMALITY

Pareto optimality is a central concept in game theory which actually has already disseminated into the engineering field.

Since Pareto optimality concepts were first developed for use in welfare economics, optimality was traditionally defined in terms of resources. With a finite amount of resources, Pareto optimality is reached when no player’s allocation of resources can be increased without decreasing some other player’s allocation of resources. Pareto optimality is therefore desirable, and is often set as the ultimate goal[25] (unlike a dominant strategy, which may result in an undesirable scenario such as N-N in Prisoner’s Dilemma).

Pareto optimality may be defined as any scenario where no player’s payoff may be improved without decreasing another player’s payoff. Movements towards Pareto optimality are called Pareto improvements, where one or more players’ payoffs are improved without sacrificing anyone else’s.

Pareto optimality is often shown via a Production Possibility Frontier (PPF) graph, like Figure 3.

[24] Historically there have been eras where salvors have not been satisfied with LOF rewards and provided pressure for better rewards or alternative arrangements. Most recently this has been expressed in the SCOPIC process. To succeed in changing the award levels, salvage companies need to be able to mutually deny services to Owners and underwriters. This is called a union approach and presently there is an International Salvage Union.

[25] However, note that Pareto optimality does not deal with the *equitable* distribution of resources between players. Therefore, in economics, Pareto optimality is a component of a desirable scenario, but not a complete definition of one. Pareto optimality plays a central role in Thomas Piketty’s *Capital in the Twenty-First Century* in the form of his discussions on income disparity.

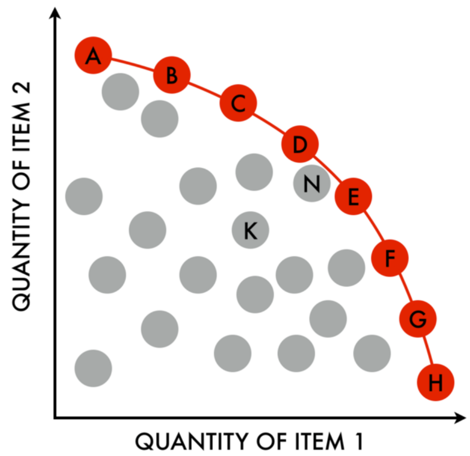

Figure 3. PPF showing points of Pareto optimality (source: Wikipedia)

Note that is Figure 3, dots A-H are Pareto optimal points, while K and N are not.

Consideration of Pareto optimalities reinforces the notion that there is no free lunch, but one can choose a variety of good lunches for a fixed amount of money. It also indicates that lack of attention (or lack of game theory knowledge) will probably result in paying good money for a bad lunch.

While traditionally the units were defined in terms of finite resources in economics, it can be readily imagined that the same concepts would apply with design trade-offs found in ship design.

In that case there are no players, but rather design features such as weight, speed, noise, environmental factors, sustainability, aesthetics, and cargo capacity, and the resource may be money.

In Figure 3 that would mean that for a fixed amount of money, Item 1could be cargo capacity and Item 2 could be speed. Anything behind the curve would still be a ship, but it is poorly designed (optimized) as compared to its cost.

The curve is also described as the Pareto Front, especially when it addresses multiple variables[26], and ship designers love the idea of cracking the Pareto Front. In design, the Pareto Front can also be called the "State of the Art"[27].

The April 2013 issue of SNAME's (mt) describes an empirical search for a transportation Pareto Front in Dr. Neu's article "Gabriella-von Karman: Updating the Plot."

[26] While still referred to as a Pareto Front, note that a three variable front would be a surface, rather than a line.

[27] If we define "State of the Art" as the optimal solution to a problem, rather than a "cost is no object" design. Either definition for the "State of the Art" is commonly used.

In Figure 4, we reproduce the plot but with an additional added front line labeled as the Neu van Hemmen limit line[28] that shows the Pareto Front for waterborne transportation.

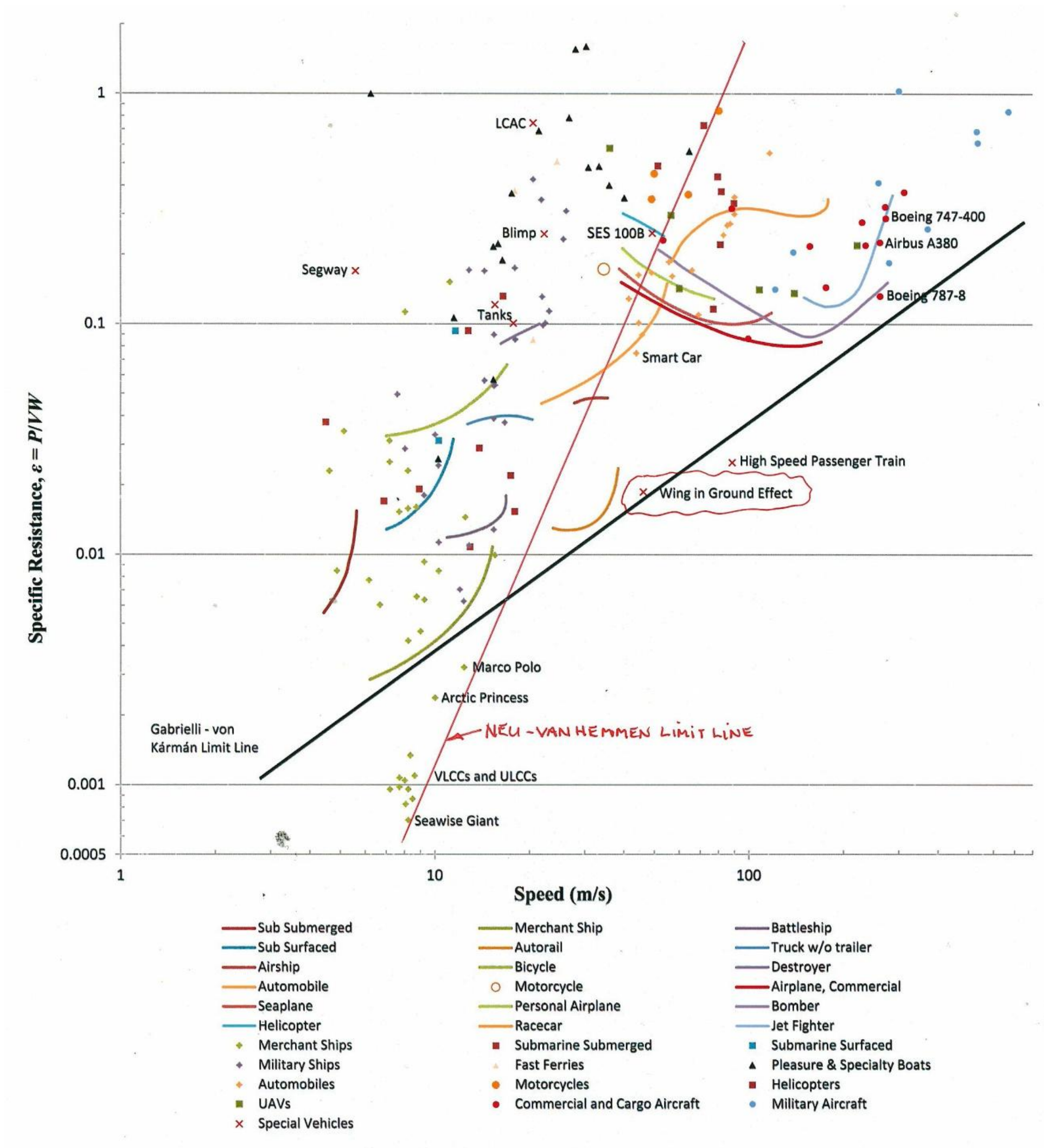

Figure 4. Gabriella-von Karman Plot updated 2013 and presented as Pareto fronts.

The underlying limiting resource for this plot is the world's transportation engineering knowledge (the "State of the Art"). As such, a major discovery in drag reduction would result in a shift in the fronts, but, so far, the only breakthroughs since the original 1950's plot are maritime increases in scale (big ships) and high speed trains (which is an exercise in drag reduction). Wing in Ground effect is circled because it shows a tantalizing technology that, so far, has failed to find a commercial application.

[28] Under the strong objection of the co-author of this paper, with regard to the main author's self-indulgence.

The classic design spiral actually describes a process that allows a designer, through multiple iterations, to approach a point along the Pareto front for a particular design. Different design efforts using the spiral may arrive at different points along the front.

Recently, Thomas McKenny and David Singer referred to Pareto fronts in their discussion of design decision making in their article in the July 2014 issue of SNAME's (mt) magazine, "Set-Based Design, a concurrent engineering approach with particular application to complex marine products".

7. NASH EQUILIBRIUM AND THE NASH APPROACH

The Nash Equilibrium concept was developed by John Nash in 1950, for which he received the Nobel Prize in Economics in 1994. The Nash Equilibrium describes a steady state between players, and can be described as follows:

Player A and Player B are at Nash equilibrium[29] if Player A is making the best decision he can make taking into account Player B's decision, and Player B is making the best decision he can make taking into account Player A's decision.

More formally, and with the possibility for more than two players, a Nash equilibrium can be defined as:

Strategy vector $s^* = s_1^*, s_2^* \ldots s_N^*$ is a Nash equilibrium if

$$p_i (s_i^*, s_{-i}^*) \geq p_i (s_i, s_{-i}^*) \qquad \text{for all } s_i \text{ and all } i \qquad \text{(Equation 3)}$$

Where: p_i = payoff of player i in scenario in parenthesis
s_i = player i's strategy
s_{-i} = strategy choice by all players other than player i
* denotes the best response

So what does that mean? In simple terms, the Nash Equilibrium is a condition where all players have made their choice and will not choose to change their choice.

The term Nash Equilibrium is introduced because it tends to be a ready identifier for decision making in non-cooperative multi-player scenarios. These scenarios occur in maritime and while the actual equilibrium tends to be elusive, the Nash approach is highly illustrative. Consider shipyard selection:

> *Suppose that there are five eligible shipbuilders for a certain type of large yacht. One builder is the most popular and is generally acknowledged to be the most capable builder of vessels of this type. The other four have declining levels of reputation but are still considered to be capable builders.*
>
> *They might initially offer the same price and all have one builder slot available.*
>
> *If there were one potential purchaser he could choose to go builder 1 and hope that there is a builder's slot available. Since there is only one purchaser, the odds of getting the slot are 100%. However, if there are five*

[29] The Russell Crowe movie "A Beautiful Mind" describes this concept.

purchasers for five slots and if every purchaser decides to go to builder 1, the odds of getting that slot are 20%[30]*. He then might choose to go to builder 2, but there would be three other purchasers and the odds would be 25%, etc. etc.*

Instead, if he went to builder 2 right away and all the others went to builder 1, he would have a 100% chance of getting a slot at builder 2. On the other hand, if all the other purchasers now adopted purchaser one's strategy, everyone shows up at builder 2!

Inherently this shows a purchaser is pursuing a moving target. However, if one knows the other purchasers' intentions one can develop an optimal strategy, and if all purchasers' intentions are known, all purchasers can develop optimal strategies.

In theory this is a helpful realization, and there are some limited cases where actual computations can be performed. Unfortunately only in a deeply cooperative society or system can other purchasers' intentions and shipyards' selection motivations be solidly modeled and, in practice, the math will be quickly overwhelmed by reality.

To date we are not aware of any Nash equilibrium or optimization efforts in shipyard selection and therefore shipyard selection (and similar processes like charter party placement) remains heavily dependent on brokers and sales personnel[31].

While actual modeling of Nash Equilibriums is difficult, there can still be astonishing advantages by not selecting the most obvious choice, but rather choosing a somewhat less obvious choice. Selecting the second most desirable shipyard can result in excellent carry on benefits such as: lower purchase cost, goodwill for giving the less attractive choice a chance, less scheduling pressure, and possible future loyalty. In other words, following the herd is far from automatically an optimal choice.

Nash Equilibriums could also be interesting in fleet make-up determination (hi-low mixes of ships) in the face of competitors and may be determined through the use of neural network computations rather than strict algorithmic approaches.

The Nash approach suggests negotiations, which is heavily defined by BATNA.

8. BATNA

Within negotiation strategy, the concept of Best Alternative To a Negotiated Agreement ("BATNA") is a guiding principle.

In marine commerce and engineering, BATNAs vary depending on the stage of a maritime adventure.

The first negotiations occur at the contract negotiation stage of the adventure. In those cases there may be various BATNAs depending on the party's exposure at a particular point in time. In a charter party negotiation the best alternative to a negotiated agreement for a ship owner may simply mean a few days delays in an earnings stream with the

[30] Assuming all purchasers are equally attractive to the builder.
[31] And a cynic could argue, heavily dependent on cartels, insider trading, and bribery.

possibility of a higher daily rate later on, or it may mean that the bank will repossess his ship. On the cargo owner's side it may mean his cargo will arrive a few days later, but with the possibility that he can secure a lower daily rate, or it may mean that his cargo will have spoiled by the time he can get it to its destination. Each BATNA has an effect on the negotiation result.

These are pure negotiations, but BATNAs also show up later in the adventure. We already referred to BATNAs in the Lloyds Open Form discussion, where the adventure is starting to fall apart and where non-agreement could result in bad BATNAs on both sides (sunk ship and no income for the salvor) but that is not clearly established at that time. Note that asymmetry in known BATNAs results in leverage. If the vessel has a real (and transparent) possibility of sinking without the salvor's available assistance, the salvor has tremendous leverage. LOF prevents the salvor from taking too much advantage from this leverage. The LOF arbitration process actually aims to reveal the BATNAs after the resolution of the emergency and based on those revelations formulates the award.

Not revealing one's own BATNA and knowing another party's BATNA is an incredible advantage in negotiations, and, in theory, may be the optimal route for a party in a negotiation, but this is not always true and this leads back to the Iterated Prisoner's Dilemma and Axelrod's tenet for predictability.

A party to a negotiation that senses he has been unfairly treated will probably not cooperate with that party again, and suddenly they are engaged in a Tit for Tat scenario.

As such, a drive for fairness can enhance cooperation and efficiencies. In maritime the concept of fairness is ancient, as can be illustrated by the 2000 year old concept of General Average that, when invoked by a shipowner, activates specific rules for sharing the cost of salvage between the shipowner (and his underwriters) and all the cargo owners that are carrying cargo on his vessel when the salvage occurs.[32]

It is significant to note that negotiations are very expensive and inherently unproductive. This is why it is much more efficient to go to a supermarket to buy food at established prices than to haggle about groceries in an open market. Negotiation can achieve advantage, but the time and effort associated with them are a pure loss to trade and society.

Furthermore, negotiations are pervasive; they exist at every level of society. Negotiations vary from arguing about use of the family car with teenage children to stopping wars between nations, and can occur at multiple levels in a maritime adventure.

A classic shipping adventure starts with negotiations in the form of contracts but if success is not immediately achieved once the adventure has started, it can eventually

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[32] The General Average rules are actually quite simple, but since the rules are ancient, the practical application of the rules is complex and the application is carefully nurtured by a worldwide group of professionals named Average Adjusters. While Average is any type of damage to a ship or cargo, a true Average Adjuster does not really come into his own until he is asked to adjust a General Average.

result in litigation. Litigation is a form of negotiation cloaked with the agreed rules of the law, which attempts to prevent the use of arms. Note that litigation and warfare both also contain BATNAs.

The maritime industry actually avoids lengthy contract discussions by wide use of standard contracts (LOF has already been mentioned, but there are many standard contracts of affreightment and charter).

The marine industry functions quite well with simple contracts. This is because practices (which are actually social contracts) are well established and BATNAs on failed maritime adventures are particularly expensive[33] for all participants in a maritime context[34] and therefore relies on the cooperation of all parties even in adverse stages of the adventure.

The need for contracts can be depicted as follows:

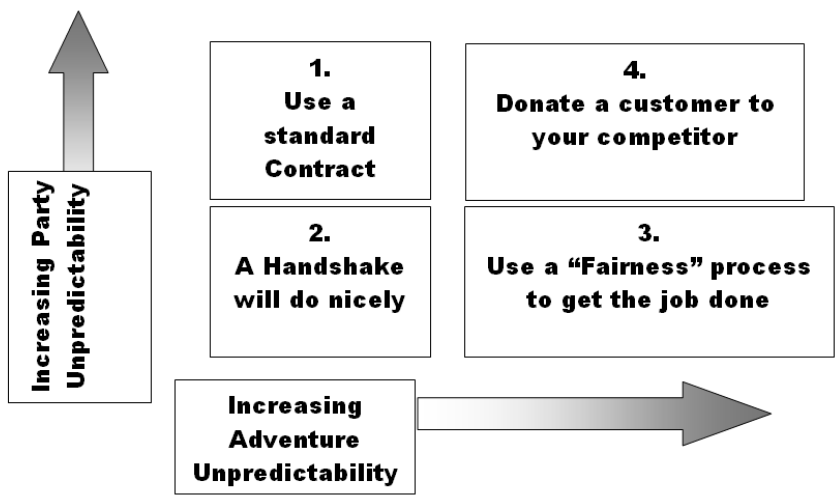

Figure 5. The Contract Matrix

A surprisingly large portion of maritime functions in Area 2 of Figure 5 because there is high transparency and actually high predictability from many iterations. If the other party is not known, a standard contract (Area 1) will reduce risk of unknown BATNA exposures.

When Admiral Rickover led the construction of the USS Nautilus there undoubtedly would have been a contract, but the entire process rested on faith in fairness between parties that knew each other well enough to get through the high level of technical unknowns. Initial ventures in nuclear submarine construction and operation therefore had

[33] This is because "total losses" are actually much more "total" in maritime – up to and including loss of life and all property (if your house burns down, you can escape from the house and still have the land it was built on).
[34] See Scene III of the Merchants of Venice by Shakespeare and the discussion between Shylock and Bassanio about Antonio the shipowner. Antonio is a rich man, but maybe not tomorrow.

to rely on Area 3. It also did not hurt that the BATNAs for all parties at any stage of the nuclear submarine construction process would have been quite unattractive.

Hopefully, Area 4 requires no further discussion.

9. OODA LOOP

The OODA loop was developed by John Boyd, a US Air Force officer and pilot who was a very influential thinker in the second half of the 20th century, but quite unknown in popular culture. In the engineering realm he was one of the major synthesizers of the F-16 fighter and he was also a very accomplished fighter pilot instructor. In the 1950's he developed a fighter pilot training method that he eventually named the OODA loop.

OODA stands for "Observe", "Orient", "Decide" and "Act". The loop is continuous, so it loops right back to "Observe" after the "Act" has been performed.

A novice in a fighter cockpit tends to observe enemy fighters and then freeze in panic not knowing what to do until he gets shot down. To prevent early death, John Boyd would train the novice to actively perform the OODA loop: Observe (get data), to Orient (figure out what the problem was; "what will kill me?", "what will make me get a clean shot?"), to Decide (engage the option that is most effective under the circumstances[35]), and to Act on the decision. The pilot would then observe to see what happened after the action was taken which begins the OODA process again. The trick was to perform this loop faster and better than the opponent, which would allow the pilot to get a clean shot at the opponent.

On an engineering level OODA is a simple feedback loop, and well known in most branches of engineering. As such, the basis of the OODA loop is as simple as the Prisoner's Dilemma, but like the Prisoner's Dilemma it can provide a high level of insight when exercised and, in the first instance, with even less math than the Prisoner's Dilemma.

The objective of the OODA loop is to come out of the loop ahead of the opponent[36] (or to not die in a rapidly developing situation). In fighter combat it comes down to getting a clean shot, but the goal simply depends on the competitive environment one is engaged in, and is particularly applicable in competitive environments where the action cannot be stopped[37].

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[35] In air to air combat one "act" option is to bail out, which disrupts the loop, but might prevent death. The bail decision should be part of the decision options in any OODA loop.

[36] You cannot outrun a bear – you just have to run faster than your hiking buddy.

[37] As such, OODA loops are very useful in SNAME sailing regattas, but less so in SNAME golf tournaments. Note that both of these games are traditional zero-sum games.

The OODA loop can be incredibly effective in many maritime circumstances[38]. The following maritime activities could benefit from OODA loop analysis and implementation:

1. Simple warfighting
2. Salvage engineering
3. Ship navigation
4. Multi pass negotiations (without cool down periods, which would remove the loop speed factor)
5. Ship design (which is always time dependent; no one wants to design the perfect ship after it has already been designed by somebody else)
6. Cutting edge engineering
7. Neural networks

The quality of an OODA loop is determined by the quality of the steps and the execution speed of the loop. Great data and a slow loop speed probably would not result in a winning loop and a failure in any part of the loop results in failure.

As such, the effectiveness (value, *V*) of OODA loops could actually be described in simple form as a function of step quality and speed:

$$V = \frac{R_{OB}\ x\ R_{OR}\ x\ R_D\ x\ R_A}{T_{OB} + T_{OR} + T_D + T_A} \qquad \text{(Equation 4)}$$

Where: R = reliability of step, where 1 is perfect reliability and 0 is failure
T = time to perform step

With subscripts: OB = Observe
OR = Orient
D = Decide
A = Act

Reliability for any one step is 100% if the OODA step has no flaws vis-a-vis the opponent or objective (the objective being a clean shot for fighter pilots). While reliability does not always have to be 100% for a useful OODA loop, the objective is to always a have higher overall value, *V*, than the opponent in a loop.

Failure (zero reliability) in any one component results in an OODA loop value of zero, and long performance times rapidly result in a low value OODA loop.

Underlying all four steps is a training function. If the result of the first OODA loop pass does not result in death or success, each subsequent loop adds a level of learning until

[38] Interestingly, John Boyd's methods were often ignored by the Air Force, but US Marines and Navy Seals took his concepts to heart and named him an honorary Marine. These services are quite familiar with OODA loop concepts and consider it to be part of their training.

death or success is achieved[39]. Meanwhile, the feedback loop allows for correction as long as death does not occur.

To ship designers the OODA loop exists as the design spiral[40] where each step of the spiral is an OODA loop and each trip around the spiral is also a (complex) form of the OODA loop[41]. Note that each trip around the spiral will result in Pareto improvements, driving closer and closer to Pareto optimality.

In ship navigation the Observe components of the OODA loop speaks for itself, the Orient component is the placement of the vessel relative to other vessels and ocean hazards, the Decide component is the resolution of the situation within the rules of navigation and good seamanship, and the Act component is the physical response of the vessel.

This description of navigation in terms of OODA loops is as fascinating in analyzing ship collision scenarios as it is in fighter aircraft combat.

Ships need to have relatively high OODA loop effectiveness (values) with regard to navigation. This can be achieved by high reliabilities in all steps and high loop speeds. But in ship navigation high loop speeds cannot always be achieved. On a super tanker Observe, Orient and Decide may work reasonably well (similar to smaller vessels), but the Act response time (T_A) may be so high that disaster cannot be avoided. On high speed ferries the Observe, Orient and Decide cycles need to be matched to the vessel's speed and responsiveness.

Analysis within the OODA loop context shows that certain navigational systems are more viable than others. As such, zero Observation (deaf operation in total fog) does not result in reliable navigation, but a low level of Observation (operation in heavy fog) may work with a navigator that keeps close track of her Orientation, can make rapid Decisions and has a maneuverable vessel (such as a Maine lobster boat, without radar, in a familiar estuary in a thick fog).

Naval combat can often be condensed to an OODA loop and the Aegis Combat System is a pinnacle application on many levels. It is not known if Admiral Wayne Meyers[42], the

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[39] Interestingly, first loop success is useless from a training perspective; a child that always passes his classes will have a hard time recovering from failure.
[40] The design spiral is an excellent example of the training function. A designer who has gone through a similar design spiral a few times no longer needs to enter at the conventional outer edge, but instead can make a very valid first pass much further into the spiral (much to the frustration of less experienced designers).
[41] Ship design has more variables and a less linear decision making process than a combat OODA loop, which is why the really great ship or engine room or aircraft designers deserve the same mythical status as ace fighter pilots.
[42] Greatness comes in many forms, but very few engineers have had a US Navy ship named after them while they were still alive.

technical father of Aegis, was aware of John Boyd's work, but Admiral Meyers' approach on Aegis is an uncanny application of OODA[43] concepts.

> *In the 1960's, Admiral Meyers became aware that shipboard missile systems had very limited lives due to component obsolescence. A missile system is basically an OODA loop. It consists of an Observe component (radar), an Orient component (displays) a Decide component (threat evaluation) and an Act component (the missiles or other armaments). In the 1960's a new development in just one part of a missile system would make the whole system uncompetitive. Since these systems did not have any modularity, an entirely new missile system would have to be developed, built and installed and at commissioning the system would already be outdated. Admiral Meyers' Aegis approach simply (hindsight is always simple) looked at shipboard missile systems as a plug and play approach and inherently allowed component upgrades without negatively affecting other components or the entire system. His approach resulted in a revolutionary (and long term cost efficient) combat system.*

The Aegis Combat System interconnects and speeds up the OODA loop steps. That, by itself, is not particularly novel and has been the aim of combat systems for many years, if not centuries, but by taking a modular approach Admiral Meyers not only applied the OODA loop to the functionality of the system, but also to the technical improvement of the system. The modular approach allowed him increase the overall system OODA value by improving reliabilities or response speeds in any of the components at any time.

Admiral Meyers drove the system even deeper by adopting the "Build a Little, Test a Little, Learn a Lot" approach which, in essence, is the substitution of many rapid OODA loops in the design and development of the system instead of thinking of the design of the system as one big (long duration) OODA loop.

This approach also resulted in a relatively low cost anti ballistic missile (ABM) system (which was not a planned feature of the original system) after hundreds of billions of dollars had been spent on other ABM systems with inherently weak OODA loop features both in the design and the actual value of the system.

Marine salvage, by itself, also operates in the OODA realm. It is a rapidly developing situation similar to navigation, or combat, and skilled salvage masters display excellent OODA skills. But salvage tends to operate with tremendous handicaps in the Observe and Orient phases and therefore salvage does not always succeed in the first loop. Today, salvage tends to operate in the public eye and lack of understanding of the nature of salvage (in salvage nothing is certain to work) can result in unproductive and often ignorant press coverage when success is not achieved on the first pass.

One of the authors was engaged in such a salvage effort (MV New Carissa, 1999) in an engineering capacity, when the general press routine was heavily focused on post mortem

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[43] It is important to note that OODA is something people have been doing at various levels since they descended from the apes and actually a reasonable case can be made that dogs function in the OODA realm too. However, any concept in game theory is something that people have likely been doing for years - the formalization of these concepts in game theory allows further study, the ability to rapidly communicate the findings to take more effective advantage of those concepts, and application of the concepts in less obvious or more complex situations.

analysis of unsuccessful salvage attempts. The author was asked how this issue could be addressed and it became apparent that the issue was the result of a lack of visible salvage activity between subsequent salvage attempts. In other words, when an OODA cycle was in the Orient and Decide phase (the Decide phase in modern salvage tends to be heavily controlled by various review stages of a plan by government agencies), the press had a field day reporting on the lack of activity and interpreted that as incompetence[44].

Within the salvage team it became apparent that instead of running a continuous single OODA loop, there should be a simultaneous second OODA loop that follows a somewhat alternate approach (a Plan B). As soon as Plan A reverted to the Observe, Orient and Decide phases, Plan B would be in the Act phase and provide sufficient press interest to contain the Monday morning quarterbacks. As such, an external driver resulted in two nested OODA loops rather than a single OODA loop.

In the time domain this can be represented as follows:

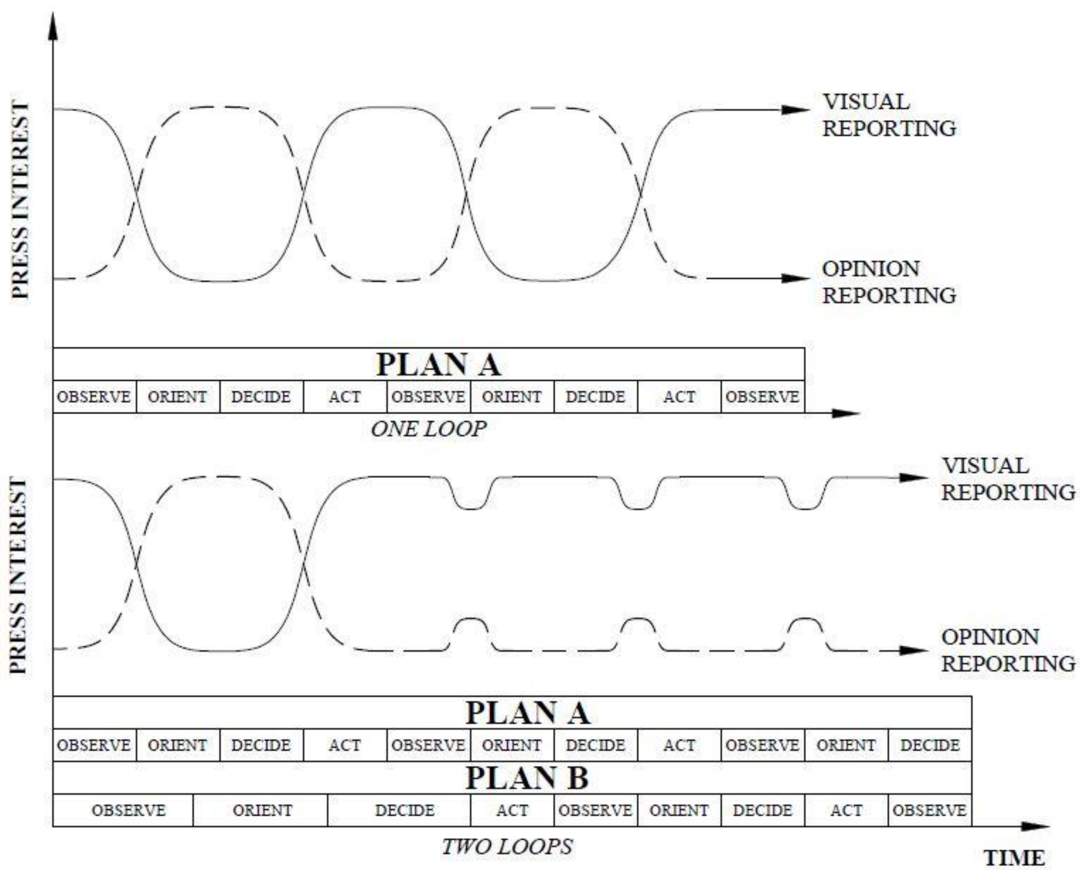

Figure 6. Effect on press coverage using a single OODA loop compared to two nested OODA loops

[44] This same problem also occurred in the Deepwater Horizon response effort.

Not all scenarios allow this approach (if Observe always depends on the result of the prior Action, it is impossible to build an independent OODA loop with the same objective), but if there are sufficient resources in a salvage situation, occasionally a second semi-independent OODA loop may be effective, both with regard to ultimate technical objectives and with regard to public relations objectives.

10. APPLICATIONS & LIMITATIONS

This paper has shown various applications of game theory concepts in maritime. In practice, an engineer conversant with these concepts will use them, and combine them, in real life situations. The ultimate effect is that an engineer, with a level of familiarity of these concepts, can more rapidly synthesize solutions and develop solutions that are more rugged and effective.

However, one very important caution needs to be provided. Central to all game theory is the need to start with effective data[45] and goals. The application of game theory is pointless if there are no reliable data and goals.

This may be inherently apparent to engineers, but even engineers may be drawn into the game too deeply and fail to make proper observations. Failure to make proper observations simply starts a pointless OODA loop (i.e. an R_{OB} value of 0 in Equation 4, which results in an overall OODA loop value V of 0).

Data is everywhere, but often important data is ignored and bad data accepted as true. Similarly, engineers deeply engaged in their game may lose sight of their objectives. It is important to realize that failures are also data points and should not be ignored. Often failures are related as stories to engineers, and story telling has been found to be incredibly important in highly skilled, complex professions[46]. Stories require vocabularies and good vocabularies result in more effective stories. Game theory concepts enhance vocabularies, enabling more effective distribution of stories in the decision making realm.

We will therefore illustrate the application of data and game theory with a joke to show how engineers can be distracted from their goals, and a real life story of the same concept.

An engineering joke:

> *During the French revolution a doctor, a lawyer, and an engineer were condemned to death and were to be executed with the Guillotine. The doctor was to be executed first and was asked if he wanted to be executed facing up or facing down. The doctor concluded he had seen enough misery and wanted to be executed facing down. The lanyard was pulled and the blade stopped within an inch of his neck. Even though it had not killed him, the sentence had been executed and he was*

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[45] It is interesting to note that game theory allows some decision making with unknowns (limited data), but cannot accommodate incorrect data.

[46] See *Sources of Power*, which argues very convincingly that story telling is central to training and since beer and stories go together, beer (in moderate quantities) is actually very important to training.

free to go. The lawyer was asked how he wanted to be executed and he too chose to be executed facing down, hoping the machine would fail again if he changed as little as possible from the prior failure. The lanyard was pulled and, again, the blade stopped within an inch from his neck. The engineer was next. When asked how he wanted to be executed, he immediately chose to be executed facing up. He was put in the block and before the lanyard was pulled he said: "Oh, I see what the problem is!"

Real life:

The Titanic struck the iceberg, and there was immediate flooding. The entire engineering staff ran to the engine spaces and started innumerable OODA loops in an attempt to keep the vessel afloat, to keep the pumps running, and to keep the lights on.

The engineering staff was incredibly effective and the vessel's lights were still on when the vessel took her final plunge, and this made the Titanic engineers enter history with the highest regard and praise for their skills, courage and actions. However, both on an engineering, and a game theory level, the Titanic engineers' OODA loops were not properly designed. Somewhere in the Observe, Orient, Decide and Act loop there should have been some consideration of Pareto optimalities, BATNAs, Nash Equilibriums, and Prisoner's Dilemmas that should have resulted in a properly timed "abandon the engine room" option. Since there wasn't, every single engineer aboard the Titanic went down with the ship.

Remarkably, in the official report for the Costa Concordia incident, the engineers did achieve the "abandon engine room" objective and were still praised for their actions. Unlike the Master, they did not prematurely abandon ship and stayed on until the very last moment when there was no other decision in the next OODA loop but for them to save their own lives.[47]

11. CONCLUSIONS

Engineering in all its forms is problem solving. Good data, clear goals, and rigorous analysis result in solid solutions. In the end it does not matter how an engineer performs a rigorous analysis, but only the solid solutions count. With proper application, a little game theory can help in achieving better, faster, and more robust solutions.

12. ANNOTATED BIBLIOGRAPHY FOR FURTHER READING

There is a substantial amount of literature on game theory that ranges from popular writings to deeply technical writing. The following literature has proven to be both useful and occasionally entertaining and further discusses the concepts in this paper.

1. *The Evolution of Cooperation*, by Robert Axelrod, 1984, is both a pleasant read on the Prisoner's Dilemma and an eye opening book on nature and human interaction. Make sure to obtain the 2006 edition with the Richard Dawkins foreword, which, by itself, is a fascinating read.
2. *The Mind of War*, by Grant T. Hammond, 2001, is the biography of John Boyd, the father of OODA.

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[47] The final report for the Costa Concordia incident can be found at http://www.safety4sea.com/images/media/pdf/Costa_Concordia_-_Full_Investigation_Report.pdf. Praise for the engineering crew can be found on page 82.

3. *Strategies and Games: Theory and Practice,* by Prajit K. Dutta, 1999, MIT, is an accessible textbook, with a particular emphasis on applications of game theory – mostly economic applications.
4. *Strategy,* by Joel Watson, is one of the best known game theory textbooks, and is more technical than the Dutta text.
5. *An Introduction to Game Theory,* by Martin J. Osborne, is another well known game theory textbook, and is more technical than the Watson text.
6. *Sources of Power*, by Gary Klein, is about decision making rather than strictly game theory, but in combination with the other literature indicates that game theory is very valuable, but can only be effectively applied with good data. Pay particular attention to the missile shoot down example.
7. *Thinking Strategically,* by Dixit and Nalebuff, is an easy read on game theory geared towards business students as well as applying game theory to everyday life.
8. "Social Science at 190 Mph" by David Ronfeldt first published in Feb 2000 in First Monday, places the prisoner's dilemma in the NASCAR racing setting.
9. "Iterated Prisoner's Dilemma contains strategies that dominate any evolutionary opponent" by William Press and Freeman Dyson in Proceedings of the National Academy of Sciences of the U.S. Vol. 109 No. 26 May, 2012 is a more technical paper identifying a novel solution to the iterated Prisoner's Dilemma, and demonstrates that research on the Prisoner's Dilemma solution is still ongoing.

13. FURTHER REFERENCES

– "Tales From the Cutting Edge" by Hendrik F. van Hemmen, available from the Association of Average Adjusters of the US and Canada.

– "Game Theory for the Maritime Professional" 2013 PowerPoint presentation, by Hendrik F. van Hemmen, available from the Society of Marine Port Engineers.

– "The Joint Field Survey Process: Multi Party Joint Forensic Engineering Investigations in Litigation and Mediation/Arbitration" by Hendrik F. van Hemmen, June 2000, Volume XVII No. 1 issue of the Journal of the National Academy of Forensic Engineers (text also available on www.martinottaway.com)

– Google Books Ngram Viewer. Publicly available computer program. Searching for various game theory terms (Prisoner's Dilemma, Iterated Prisoner's Dilemma, Tit for Tat, OODA, Pareto Front, Nash Equilibrium, Pareto Optimality) provides an interesting insight in the history of game theory. Bear in mind that Batna is also a city and a province in Algeria and therefore does not search well.

– *Peacemaker*, www.peacemakergame.com, a computer game that simulates the Israel/Palestine conflict. The objective is to achieve peace. When playing the game, it becomes apparent it relies heavily on the concepts described in this paper. Use game theory and you will make peace (in the game at least, but the lessons are real). The design assumptions can also be found here: www.impactgames.com/blog/2006/12/22/peacemaker-design-assumptions.

– *John Boyd Compendium*, a collection of documents by John Boyd, including his work on the subject "A Discourse on Winning and Losing". Available via Defense and the National Interest.

14. ACKNOWLEDGEMENTS

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