Using Stakeholder Value Analysis to Build Exploration Sustainability

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Abstract: The sustainability of space exploration will depend in large part on its ability to consistently and reliably deliver valued benefits to societal stakeholders over an extended period. This on-going research studies the values of prospective stakeholders in the space exploration enterprise—both in the near term and with a perspective extending over decades. The immediate focus is human and robotic exploration of the Earth/Moon system, but extends to the exploration of Mars as well. Potential beneficiaries of space exploration are identified in broad societal sectors. An analysis of these stakeholders, their values and needs leads to the development of a comprehensive set of space exploration objectives that address those needs. The relative priority of exploration objectives is weighted using information about stakeholder characteristics, values, and their role and place in the exploration value stream. The weighted exploration objectives can then be used to assess the relative value of different technical system architectures, and to design exploration enterprise architecture, attributes and policy frameworks to enable value delivery to societal stakeholders. Ultimately, through stakeholders' continuing support, sustainable space exploration will be delivered.

I. Introduction

A critical aspect of future space exploration must involve considerations of sustainability. Technical success alone cannot ensure that space exploration will have the continuing societal support necessary over the course of decades to develop enduring and expanding exploration capabilities. To ensure that the exploration system is sustainable, it must also produce valued outputs (e.g., knowledge) and deliver them to a wide spectrum of societal beneficiaries (such as the public). All stakeholders must be aware of the benefit and of its delivery. This flow of valued benefits to stakeholders is the exploration value delivery system.

Besides the flow of valued benefits to stakeholders, there are at least three other factors that contribute to sustainability. Policy robustness addresses the way in which the exploration enterprise interacts with its external environment, including key government resource-providers, so as to assure continuing support for exploration activities. Next, risks of exploration must be understood, explicitly minimized, and residual risk clearly communicated to all stakeholders. Finally, the exploration system must be affordable, its multiple elements acquired and operated within a realistic budget. The combination of value, policy robustness, risk management, and affordability contribute to assuring that societal stakeholders will be informed of the costs and benefits of space exploration, and that benefits exceeding costs will be delivered to them consistently over the period of years and decades required to achieve a robust exploration capability.

We propose that a sustainable exploration value delivery system results from deliberate design decisions, and that those design decisions are best realized through an understanding of the system's stakeholders, their values and needs. Once values and needs are identified, system objectives can be defined, leading to the development of specific architecture choices not only for the exploration technical system, but also for the exploration enterprise and

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operating concept, as well as its policy environment. The exploration enterprise includes the core set of explorers, scientists, and engineers that realize and execute the space exploration campaign. It also includes the extended group of stakeholders who are not directly involved in the exploration campaign, but who are nevertheless crucial in providing support and funding. This enterprise architecture and operating concept includes core government organizations and extended network of affiliated suppliers; designated responsibilities, authority, and accountability among enterprise stakeholders; the culture and artifacts of high reliability operations; the structures, policies, and tools for evolutionary system and evolutionary *system of systems* (SoS) development; and the necessary infrastructure to enable completion of primary missions and to provide robust exploration capability over an extended period.

This paper is an interim report of the development and application of a process for designing an enterprise value delivery system, including development of the necessary background information. It is best characterized as the first spiral in a multi-spiral development effort, the ultimate objective of which is the development of techniques for expanding the repertoire of tools and techniques available to system and enterprise architects. While this discussion is focused specifically on the space exploration value delivery system, we are confident the concepts can be applied generally. We begin with a discussion of the stakeholders in the exploration enterprise and their stated, revealed or implied needs. This is followed by a process for translating those needs into specific exploration objectives. From those objectives, a process for establishing priorities is demonstrated. From prioritized objectives, the development of specific technical, enterprise, and policy architectures is shown. Examples from the underlying research are provided throughout to illustrate the steps in the process.

II. A Stakeholder Value Approach

Stakeholders are the core constituents of the exploration enterprise. They provide resources, support, employees, technologies, and ultimately govern its activities. It is fitting that we begin our analysis with them. We look to existing research on stakeholder theory to help frame the inquiry and identify specific processes for identifying space exploration stakeholders and their needs.

A. Stakeholder Theory

Resurgence of stakeholder theory as a governance and management approach is attributed to R. E. Freeman's arguments in his *Strategic Management: A Stakeholder Approach*[1]. This work spawned two decades of theorizing and research on the subject. Since then theoretical and empirical work has centered on diverse approaches to understanding the proper role of stakeholders, stakeholder management and the relationship of these concepts to ethics, performance, and other factors relating to enterprises. Freeman summarized the thrust of his work: "if organizations want to be effective, they will pay attention to all and only those relationships that can affect or be affected by the achievement of the organization's purpose."[2]

The fundamental issue in stakeholder theory centers on the proper basis for management and governance of enterprises. It boils down to the question: "What is the best way to govern [an enterprise]?"[3] Traditionalists tend to advocate a single valued objective function approach, which results in maximization of shareholder value as the measure of success. Stakeholder theorists argue that this guideline is too narrow and exclusive, that it does not allow managers to address effectively the multiplicity of interests that inevitably impact and are impacted by an enterprise. We agree and for the purposes of this research strive to preserve transparency on as much information about stakeholders and their needs as possible through the on-going analysis. This position generates many questions such as: "How are stakeholders identified?", "How are their needs discovered?", "How does management adjudicate when inevitable conflicts in stakeholder interests arise?", "How fine grained should stakeholders be divided?", "How can enterprise management judge whether their performance is benefiting stakeholders in the most efficient or effective way possible?" become central.

Unfortunately, despite many years of effort, researchers have been unable to definitively test stakeholder theory[4]. In addition to empirical difficulties, researchers have been unable to converge on consistent definitions and conceptualizations of stakeholders, stakeholder theory, or stakeholder management[5, 6]. Some have argued that much of this debate is clouded by ideological and philosophical views on the legitimate purpose of enterprises in society, specifically profit-seeking enterprises, with emphasis on the relationship of stakeholder theory to business ethics[7, 8, 9, 10, 11].. There is research that addresses these questions, but no consensus as yet on the utility or validity of it. In addition, it is not apparent that the compendium of research and theorizing addresses other pertinent issues such as how stakeholder interactions with each other may or may not influence whatever enterprise objective function(s) arise from application of stakeholder theory and management. In general, past research provides no clear-cut guidance on a process to identify and assess stakeholders and their needs.

Our purpose is practical and narrow: "How can we architect a *public* enterprise that must accommodate numerous (possibly conflicting) views and ideas about how it should achieve its defined mission?" Indeed, over the course of the exploration enterprise's life-span its mission may change because of stakeholder actions and interactions. So we must ask and answer for ourselves questions such as "Who are the stakeholders?"; "How can we gain insight into their interests and values?"; and "How can we simultaneously address what are certain to be conflicting interests and values among the various stakeholder groups?" This focus eliminates a number of areas of prior study on stakeholders.

Intuitively, we believe that the relationships between various stakeholders generates additional dynamics that extend beyond the collective group, dynamics not directly addressed by stakeholder theory but which are an important part of the value exchange relationships that exist in extended enterprises. Evolving research on Lean Enterprises (to which some of the authors are party) provides some guidance. Murman, et al[12]., defines a lean enterprise as "an integrated entity that efficiently creates value for its multiple stakeholders by employing lean principles and practices." The concept of Lean has more traditionally been associated with manufacturing and the Toyota Production System[13]. However, the evolving and expanding definition of Lean has grown to encompass entire organization systems where the ultimate goal is to have an enterprise that is "dynamic, knowledge driven and customer focused…continuously evolving with its environment, seeking improvement and perfection[14]." One of the primary tools in lean enterprise research is value stream mapping, a direct correlate to the exploration value delivery system mentioned previously. Enterprise value stream mapping identifies stakeholders, their relationships to one another, their needs and relevant attributes. We draw on these evolving tools and concepts from the lean enterprise literature as a starting point for this analysis.

The additional challenge posed by the space exploration enterprise is that it is large, extensive, and not all stakeholders relate to each other in a hierarchical or contractual fashion as they might in a business enterprise. Each stakeholder can uniquely influence other stakeholders and the overall exploration activity depending on how directly they are involved, how they relate to the others, and what roles they play. Kochan and Rubenstein[15] identify two general classes of stakeholders: definitive and latent. According to Kochan and Rubenstein there are three key criteria for categorizing stakeholders: (1) Stakeholders must hold assets that are critical to the enterprise's success; (2) Stakeholders must put their assets at risk in the enterprise; (3) Stakeholders must have sufficient power to compel influence. In Kochan and Rubenstein's framework, stakeholders must meet all three criteria to be classed as a definitive stakeholder, otherwise they are latent. In our work we replace the adjective "definitive" with "direct" and "latent" with "indirect". Whether a stakeholder is direct or indirect will become an important consideration later as we attempt to prioritize needs.

B. Exploration Stakeholders

Using these concepts to identify stakeholder groups, we identified thirty-two groups at the beginning of our analysis. These ranged in size and character from the relatively small and focused "Space Crew Explorer" group to more diffuse groups such as "Public" and "Media". As our analysis proceeded, it became increasingly difficult to address enterprise and exploration objectives effectively for this limited, but large, number of stakeholders. In addition, we discovered that many stakeholder needs were similar to other stakeholders or overlapped with each other. For these reasons we aggregated into more general stakeholder groups. For example, the many US government agencies which may be considered stakeholders were aggregated into a group called "Other USG Agencies", commercial enterprises with different interests were grouped as "Commercial enterprises" and the space crew, earth operator and scientist explorers were grouped as "Explorers".

From this aggregation, we obtained thirteen stakeholder groups. These stakeholders constituted the core group on which we performed our analysis of needs and developed exploration objectives. Even with this reduced number, the task of integrating and tracking values and needs to stakeholder objectives required further aggregation. For the technical system and enterprise architecture analyses that will be explained later, it is helpful to have even fewer categories of stakeholders. To that end, we identified five general categories of societal interests, which are listed in Table 1. These categories include both direct and indirect stakeholders of space exploration. Table 1 shows the relationship between the top level societal interest groups and the stakeholders we identified. Note that some of the stakeholders appear in multiple interest categories. This is not surprising, given that any stakeholder group represents an amalgam of complex motives and interests.

Exploration	Science	Economic	Security	Public
Explorers Engineers NASA	Scientists NASA Other USG Agencies	Commercial enterprises Other USG Agencies Engineers	DoD Intelligence International Partners	US Public Media Educators Executive Branch Congress NASA

Table 1. Societal interest groups for space exploration.

C. Stakeholder value identification

Starting with our earliest identification of stakeholders (the list of thirty-two), we undertook a comprehensive search to identify values and stated needs. For some stakeholders, the values and needs data were relatively abundant or easy to find; others were more challenging. For example, the President, as a representative of the Executive Branch of government as well as the American Public, has clearly stated his values in "A Renewed Spirit of Discovery", the current Administration's vision for space exploration[16]. Congress (and, by proxy, the Public) have also identified their values, stated in the Space Act of 1958 (as amended), in, addition to the plethora of public opinion and polling data over the decades of the U. S. Space Program. For other stakeholders, such as some government agencies, defining needs was more difficult. For example, the Department of Energy is classified as an indirect stakeholder and identifying its needs required research into budgetary and strategy documents and inference of needs based on the contents of these documents. The stakeholder values and stated needs formed the starting point for our development of exploration objectives.

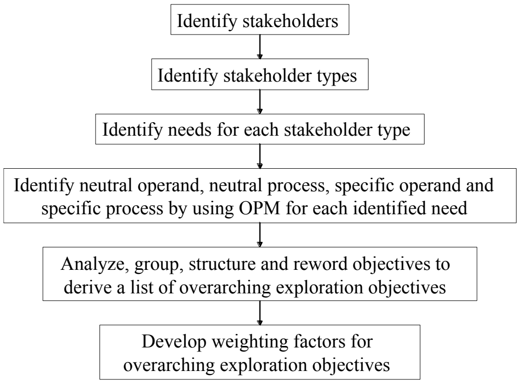

Figure 1.Defining preference-ordered objectives from stakeholder needs.

As an example, our analysis of the Executive Branch/President as a stakeholder group, identified nine different needs deriving from history, legislation (Space Act), the current Space Vision and other data such as public opinion polls and archives of past Presidential statements and actions regarding the Space Program. From these sources, we developed the following "needs" for the Executive Branch/President: promote economic growth; demonstrate national leadership (maintain and grow political capital); maintain national security; demonstrate global leadership (maintain and grow international political capital); show progress on the Space Vision; demonstrate good stewardship of national treasure and U.S. interests; contribute to planetary protection from extraterrestrial threats to existence (asteroids) and to get re-elected. At this point in the process, we identified on the order of 100 specific needs statements for all stakeholders[††].

III. Using Object-Process Methodology to Derive Exploration System Objectives

Having identified stakeholders and their needs, we then proceeded to identify the stakeholders' exploration-related objectives, to which the exploration technical architecture and value delivery system are to be designed. An overview of this process is shown in Figure 1. Object Process Methodology (OPM) was used to represent formally the identified stakeholders, their needs, and various ways those needs could be met. OPM combines formal yet simple graphics with natural language sentences to express the function, structure and behavior of systems in a

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[††] Providing an approximate rather than definite number of stakeholder needs does not imply that this process lacks rigor. Stakeholder need identification is a highly iterative process and the number of specific stakeholder needs is dependent on the best-available information about that stakeholder at the time. Since needs and information about them changes with time, and with evolving contexts, the categorization criteria generally change as well. Providing a specific number of stakeholder needs would only provide a snapshot, which fails to convey the dynamic nature of this research process.

single, integrated, model. It also allows us to flow from objectives through concepts to specific implementations (or form)[17, 18]. The graphical models in OPM are called OPD (diagrams), with corresponding text-based descriptions of objectives written in OPL (language). OPD is built from three basic types of entities: objects, processes and states, with objects and processes being higher-level building blocks. Objects exist (with state descriptions), and processes transform objects by generating, consuming or affecting them. A generic demonstration of this approach is in Figure 2, which shows value flow from stakeholders to a specific system solution.

OPL:

- To (neutral process)
- [attribute of neutral process]
- the (neutral operand)
- By (specific process)
- [attribute of specific process]
- using (generic system concept) [and/or] (specific system form)

OPD:

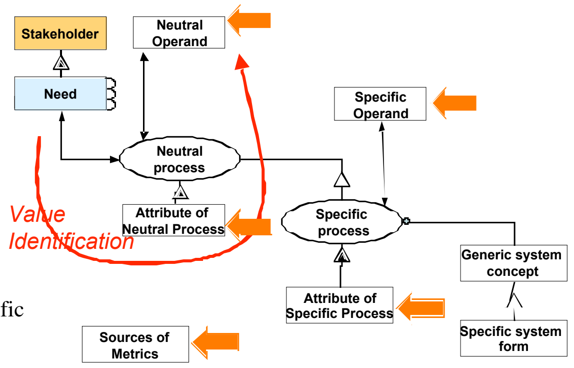

Figure 2: Generic OPM process artifacts.

Figure 2 shows generic versions of both the OPD and the objective statement, in OPL, representing both graphic and textual description. For each stakeholder need, the question is asked 'what should be transformed so that the stakeholder need can be addressed?'. The answer to that question, in a 'value neutral' context derives the neutral operands. The neutral process acts upon the neutral operand in order to address the identified need. The specific process represents a way in which the neutral process can be done. A specific process may also act upon a specific operand. A generic system concept is an instrument to run a specific process. The specific system form is one instance of form the generic system concept may take. Attributes qualify a neutral and specific process but are not mandatory in order to derive the objective statement in OPL. The boxes with arrows are candidates for deriving metrics by which value delivery can be assessed. Using this approach, a stakeholder and its needs, and corresponding ways by which those needs are satisfied can be presented in a compact visual form. Consequently, OPDs serve as a helpful communication device for architecting activities. Later, these OPM artifacts can be automatically converted into executable architecture models, greatly aiding architecture trade studies[19, 20].

For each stakeholder, Object Process Diagrams were created to graphically illustrate their needs and likely ways those needs would be met[21]. Figure 3 shows commercial space enterprises with a need for cheap and safe access to orbit. The OPD illustrates how this might be accomplished, with the resulting OPL: TO reduce entry barriers for businesses needing access to orbit BY developing the market for launch services.

Using this approach, the needs statements for the 13 stakeholders were represented in OPD and OPL. For each identified need, an OPL objective statement was generated. For convenience and traceability, the needs and resulting objectives were kept in a master spreadsheet. An excerpt from this spreadsheet is shown in Table 2. A stakeholder, its need, neutral operand, neutral process, specific operand and specific process are identified. From these inputs the objective statement is automatically composed, resulting in the master list of objectives for the 13 stakeholders.

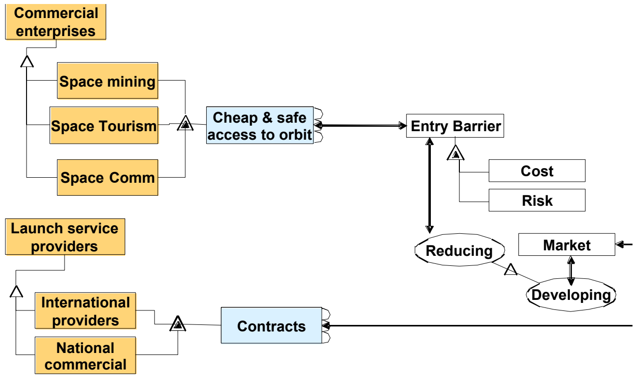

Figure 3: Example of objective generation using OPM.

Stakeholder	Need	Neutral Operand	Neutral Process	Specific Operand	Specific Process	OPM objectives	Objectives
Commercial Space Space Mining	Cheaper Space Transportation Infrastructure	routine inexpensive access to the moon	provide	Space transportation infrastructure	building	To provide routine inexpensive access to the moon BY building Space transportation infrastructure	To reduce entry barriers for businesses needing access to orbit by developing the market for launch services
Commercial Space Space Tourism	Cheaper Space Transportation Infrastructure	routine inexpensive access to leo	provide	Space transportation infrastructure	building	To provide routine inexpensive access to leo BY building Space transportation infrastructure	
Commercial Space Space Communications	Cheaper Space Transportation Infrastructure	routine inexpensive access to LEO, MEO, GEO	provide	Space transportation infrastructure	building	TO provide routine inexpensive access to LEO, MEO, GEO BY building Space transportation infrastructure	
DOD	Cheaper Space Transportation Infrastructure	routine inexpensive access to LEO, MEO, GEO	provide	with commercial space transportation partners, invesing in development, modifying federal regulations and NASA launch policy	operating	To provide routine inexpensive access to LEO, MEO, GEO BY operating with commercial space transportation partners, invesing in development, modifying federal regulations and NASA launch policy	
DOD	ResponsiveSpace Transportation Infrastructure	responsive access to LEO, MEO, GEO	provide	with commercial space transportation partners and evolved launch processes	operating	To provide responsive access to LEO, MEO, GEO BY operating with commercial space transportation partners and evolved launch processes	

Table 2: Traceability from stakeholder needs to overarching exploration objectives

The set of roughly 100 exploration objectives at the individual stakeholder level was seen to have a number of consistencies and repetitive patterns, lending itself to clustering and aggregation. Consequently, similar objectives were clustered together in like groups. Through content analysis, the intent of the objectives in each group was captured and articulated in a single overarching exploration objective statement. This reduced the number of exploration objectives to a more manageable 24, listed in Appendix A. The outcome of this process is illustrated in Table 2, where several similar stakeholder objectives are addressed by the overarching exploration objective "To reduce entry barriers for businesses needing access to orbit by developing the market for launch services."

A lesson learned from this analysis is that stakeholder objectives exist at different levels in what is ultimately a hierarchy of objectives. On-going analysis is employing a hierarchical objectives tree structure to more rigorously cluster stakeholder objectives and define overarching exploration objectives. An additional lesson learned is that these overarching objectives statements are coupled with the context of the stakeholder in the value delivery system and with the functional forms in which these objectives will be met (e.g., the technical architecture of the exploration system). While the underlying needs of stakeholders don't change (at least in the short term), the way they are categorized for this analysis may change as it becomes more clear how those needs will be addressed. Consequently, this is an iterative analysis process that benefits greatly from concurrency in the development of the technical, enterprise, and policy architectures and their roles in the overall value delivery system.

IV. Developing a Precedence Order for Exploration Objectives

The scope of stakeholders included in this analysis revealed many different and not always aligned priorities with regard to space exploration. Not all objectives that were identified can, or necessarily should, be completely met. The creation of successful technical and enterprise architectures will require balancing the interests of some stakeholders with potentially competing interests of others. This challenge is compounded by the sheer number of stakeholders and objectives that must be considered. To define a single value delivery system (including, e.g., technical architecture, etc.) that will meet those objectives, the architect must simultaneously consider the importance of meeting the objective for the fundamental success of space exploration, and the value of meeting that objective to the various stakeholders involved. The former consideration addresses principally the technical success of exploration activities, while the latter addresses the support and ultimately, sustainability of the exploration activity over the long term. From these, one can place value, and hence relative priority on meeting specific exploration objectives. This section addresses considerations in prioritizing objectives relative to multiple stakeholders, and discusses the approach used here.

Research on approaches to define precedence ordered objectives when dealing with multiple stakeholders has been done for more than 50 years. One seminal result in the field is Arrow's Impossibility Theorem[22], which states that it is impossible to design a fair method for prioritizing objectives in a way that would obey every criterion required by a group of stakeholders. It specifically states that it is not possible to find a general method (compatible with the non assessed context) to transform the preferences of more than 3 individuals into a global precedence order, without resorting to a dictator (someone who declares priorities by fiat.) Consequently, any attempts to define global preference sets can at best only approximate the collective interests of all stakeholders with some error, and will likely benefit some stakeholders at the expense of others.

While a perfect method does not exist, some attempts have been made to find compromise solutions. The Analytic Hierarchy Process, or AHP is a preferred tool when it is possible to gather a group of people that are accepted as the ultimate decision makers for a system or concept[23]. The process builds a matrix of pairwise comparisons of different objectives to be ranked, assigning weights to the relative importance of one over the other. Through the eigenvalues of this matrix it is possible to find weights for the objectives and assess the consistency of the comparisons themselves—it is self-diagnostic. The use of pairwise comparisons to create ordinal ranking is the primary weakness of this approach. Decision-makers are inherently limited in the number of simultaneous comparisons they can make. In order to accommodate large decision spaces with numerous objectives, hierarchical layers must be imposed which can become unwieldy and potentially introduce sources of error. In this analysis, using an AHP process would require roughly 280 comparisons for each stakeholder, resulting in over 3500 pairwise comparisons. While theoretically sound, this approach presented significant problems that rendered it impractical in this instance.

Multi-attribute utility theory (MAUT) potentially relaxes the requirement for pairwise comparisons, overcoming the significant challenge of large-scale systems. It addresses the challenge of multiple stakeholders through a deliberative process where "experts-representatives" negotiate for needs they represent, and find consensus through a group process[24]. While encouraging, this process is best used where a relatively small number of stakeholder representatives can directly negotiate a solution. The case of space exploration is particularly challenging because of the size of the endeavor, as well as the difficulty in representing broad stakeholder categories with a single expert. The general identification of interests, objectives, policy trends, etc., for the stakeholder groups we are interested in can be found in written documents, which allows for a deep and wide representation of stakeholder's objectives. However, finding real experts who would reflect the particular and complete perspective of each stakeholder and who would be available for the extensive negotiations necessary to develop consensus would be impractical as well.

Because of the limitations in the previously-mentioned approaches, we used a Direct Assessment method of allocating points to each objective. This follows the techniques used for the Quality Function Deployment[25] and several similar approaches to build a matrix to assess the strength of the benefit for each stakeholder/objective pair. While the Analytic Hierarchy Process was ruled out, we used a bilateral agreement technique among pairs of researchers, asking pairs of researchers to derive the weights of the different objectives for each stakeholder. This technique is derived from research that shows that a bilateral agreement under some conditions is enough to approximate the consensus of a complete group[26].

Deciding what criteria to use to evaluate how much each stakeholder values a particular objective is not a simple proposition. A neoclassical economic perspective on value is that individuals' preferences (i.e., values) are only revealed when they exchange one item for another. A transaction-based perspective on space exploration would address not only the benefit that space exploration provides to a certain stakeholder, but also what that stakeholder provides in return for that benefit. An example of this might be that the publicity associated with space exploration is valued enough by a firm that it is willing to underwrite the cost by providing fees for advertising in association with a space mission. Given that exploration may unfold over time and stakeholders may not reciprocate for some time, a temporal element should be added to a transaction-focused approach (net-present value calculations are an example of applying a temporal dimension to activities for which payback may take some time.)

Another economic perspective that applies to space exploration is that it is a public good. No one stakeholder will directly benefit enough to make investments in exploration activities, so it is the role of government to address the market failure by investing directly and allowing the benefits to flow to stakeholders in accordance with their respective priorities. This approach is helpful when the support for an activity is diffuse and the risk/reward profile is sufficiently obscure so as to prevent market-based funding mechanisms, as is the case with space exploration. An important consideration for governments investing in public goods is the likelihood that there will be an eventual payoff from the investment.

Absent existing theory or practice on determining multi-stakeholder utility in large-scale value delivery systems, we used multiple criteria to assess how the stakeholders we identified would value or prioritize the overarching exploration objectives. We used teams of 2 researchers who were well-versed in the priorities and objectives of a particular stakeholder to estimate their affinity to a particular objective by answering the following questions: Impact: "*How much will the benefit delivered by exploration align with the stakeholder's values?*". Return: *What kind of benefit impact is this stakeholder able to deliver back to exploration activities if this objective is met?* Lag: *What is the time frame in which the stakeholder will be able to deliver benefit back to exploration activities if this objective is met?* Ease: *How easy is it to satisfy these objectives through an exploration program focused on the moon and Mars?* We used a simple ordinal scale where the score was 0, 1, 3 or 9 for a no, minor, intermediate or strong relation, respectively, between the stakeholder and overarching objective (negative values were used to indicate a negative relationship.) This scale and approach to scoring is fairly widely used in a variety of direct assessment methods. The resulting 4 stakeholder by exploration objectives matrices (1 for each question answered) were used as potential input to the preference ordering process.

The preference weight for an objective based on exchanges between stakeholders is simply the product of all 4 criteria (Impact, Return, Lag, Ease), based on how much the stakeholder values meeting the objective, is willing to pay for it, the time over which that return will occur, and the ease of providing the benefit to that stakeholder. A public good-based weighting factor is simply the product of the Impact and Ease scores (because there is no expectation of reciprocity in that approach.) A simple average of all stakeholders' scores for a given overarching exploration objective provides an overall weight or preference for meeting that objective in the exploration value delivery system.

In reality, we know that not all stakeholders are equal. Some are direct participants and some are indirect participants in the value delivery process. Some of the stakeholders receive value from exploration activities through intermediaries such as the news media or educators. A simple average is not an accurate way to calculate preferences for meeting objectives. The structure of the value delivery system and the relationships between different stakeholders play a critical role in determining overall priorities. This requires insight into the value stream of the exploration enterprise. Without an understanding of the relationships between stakeholders, an exchange-based approach to calculating preferences lacks adequate information to be accurate. Consequently, as an interim solution we used the measure of correlation between a stakeholder's values and the objective (Impact) to calculate preference weightings.

The matrix that results from this process presents a map of stakeholders' preferences for seeing different objectives accomplished. While this matrix includes all the information that links stakeholders with objectives, the societal interest categories are more helpful to architecture decision makers because they present fewer categories of information for consideration. In light of the discussion above on the impossibility of creating global preference orders without arbitrary intervention, this approach is preferable to creating one single weight for each objective. The preference weighting for each overarching exploration objective in each societal interest category is simply the average of the scores of all stakeholders within that category. This grouping resulted in a compact matrix, where each societal interest category has expressed preference rankings for the overarching exploration objectives. This allows decision makers to evaluate different competing architectures through complementary quasi-orthogonal dimensions. The resulting matrix is shown in Appendix B.

In summary, this approach provides results, but is not entirely satisfactory. We consider it a first approximation to a generalized ranking assessment methodology we are currently developing. Our approach to addressing the challenges mentioned is to employ as much information about the system, its stakeholders, and their relationships as possible to minimize or eliminate erroneous assumptions. Lean analysis tools such as enterprise value stream mapping and analysis tools[27, 28, 29] will likely contribute significantly to this. Ultimately, a new method based on this approach may allow more information about the system to be preserved for decision makers and architects.

V. Application of Stakeholder Value to Exploration System Definition

The weighted overarching exploration objectives represent exploration priorities—information that can be used in the development of the system technical architecture, the architecture of the enterprise that operates it, and the policy environment in which they exist. To recap, weighted objectives contain at least two different kinds of information. First, the objectives in aggregate reflect the collective interests of the societal stakeholders who might directly or indirectly benefit from space exploration. In the interest of completeness, the system architect would want to be informed of all exploration objectives to assure that the eventual architecture leaves none unaddressed. Second, the weightings provide a relative prioritization for meeting those objectives, and can be used to inform the tradeoffs that are inherent in the architecting process. Additionally, our approach places exploration objectives in the context of the larger value delivery system. Their relative position is reflected by their weighting, but an overall understanding of the value delivery process provides additional insight into how best to meet those objectives. We've discussed three primary value delivery mechanisms: technical architecture, enterprise architecture, and policy.

Clearly, the technical architecture is the primary mechanism of the three for delivering mass to a planetary surface. The relative weighting of scientific, exploration, and other objectives will determine how payload mass is traded with other priorities. For delivering scientific knowledge from exploration, for instance, the value delivery mechanism is less clear-cut. Certainly, a communications and information system and associated infrastructure is needed to return data from remote exploration sites. However, the stakeholder perspective and value delivery system approach outlined so far also suggest that to deliver exploration information to stakeholders will likely require an enterprise design that includes processes, rules, and perhaps integration of stakeholders nominally external to the immediate exploration organization. Understanding what information will provide the most value to stakeholders may include political considerations that involve some elements of policy. This holistic approach requires different ways of addressing how to design the exploration system so it will best meet its objectives. The following three sections provide an overview of approaches we are using to develop a holistic exploration value delivery system. The first discusses the development of the technical architecture. The second addressed the design of an exploration enterprise architecture, while the third addresses policy.

A. Technical System Architecture

From our perspective, the technical system architecture comprises a transportation system architecture, an information system architecture and a surface operations architecture. All of these elements of the architecture have historical precedents. Consequently, the technical systems architecting and analysis for space exploration is the most mature of the three approaches we are addressing for achieving sustainability. It generally has well-developed models, analytical tools, and historical data available with which to conduct analyses. This section briefly describes the approach and tools we are using to integrate stakeholder value-based objectives with technical evaluation tools and processes.

Stake holder	Need	Objective	Aggregated Objective	Proximate Measure	Indicator Metric
Explorers Scientists	Scientific Exploration	TO Increase Knowledge gained from exploration BY conducting experiments	To increase knowledge about the solar system	Quality of Data	Recon and survey Spatial area of a given site that can be reached Diversity of sites Ability to temporally re-plan within mission (week to month) Ability to temporally re-plan and adapt in campaign
				Amount of data	Exploration payload delivered to M surface Observation days for crew on surface Observation days for robots on surface

Table 3: Illustration of technical architecture proximate metrics and indicator measure generated.

A primary challenge in using a stakeholder value-based approach as input to technical system architecting is that metrics of societal value are at a significantly different level of analysis than those necessary for effective system architecting and engineering design. What is valued varies from beneficiary to beneficiary and is hard to measure, with knowledge of values often gained through revealed preferences, which are only evident once an activity such as a mission is completed. Value can be characterized by indicative metrics, but these too may be dependent upon mission completion. The ranking of candidate system architectures takes place long before many stakeholders are even aware of a mission, let alone a technical system architecture. Consequently, architecture evaluation metrics that define a trajectory towards the outcome that will ultimately be valued by enterprise stakeholders must be identified and used. We developed *proximate measures* as a bridge between stakeholder needs and the architect's needs. We operationalized these proximate measures with indicator metrics that were directly measurable. Table 3 illustrates one such progression from stakeholder need to indicator metrics.

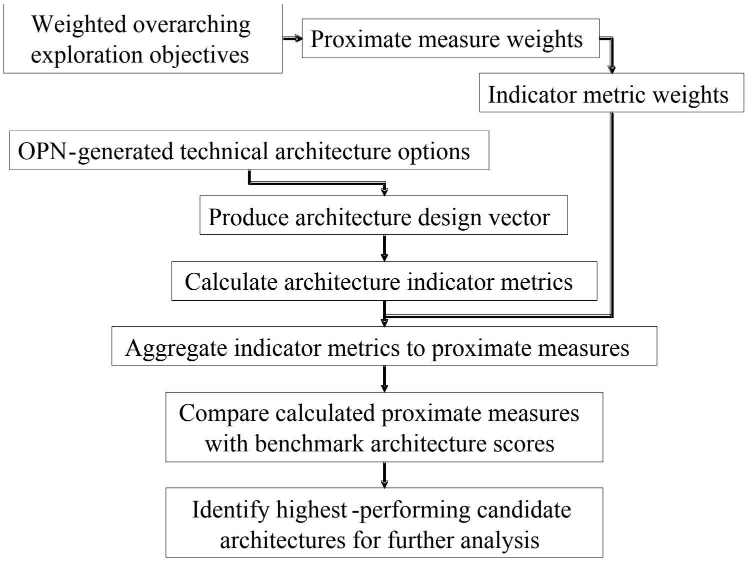

Figure 4. Flow of stakeholder-based metrics into technical architecture analysis.

Overall, 21 proximate measures for technical system architectures were derived from the overarching exploration objectives. They were designated to value, affordability, policy robustness and safety & risk categories, corresponding to the 4 primary components of sustainability. The proximate measures for value were further designated to exploration, scientific, security, commercial and public categories, corresponding to the societal interest categories outlined in Section II. Within each of these 8 categories, the proximate measures were assigned a weighting factor to reflect their relative importance in meeting stakeholder objectives[‡‡]. Consistent with not creating a global preference ranking, there was no attempt to rank or assign weights across the 8 categories. Each of the 61 indicator metrics were also assigned weighting factors corresponding to their respective proximate measures. The overall weighting factor for an indicator is obtained by multiplying the corresponding metric weight and the indicator weight. Considering the proximate measures weights are derived from objectives weights, these indicators, and their weighting factors ultimately trace their heritage back to the stakeholder value analysis, as shown in Figure 4.

The process for evaluating and ranking technical system architectures, also shown in Figure 4, is relatively straightforward. The Object Process Network (OPN) model[30], an automated form of OPM, generates the set of feasible architecture variants that satisfy the needs identified using OPM. The number of architecture variants could range in the hundreds or thousands, depending on the parameters of the OPM. For each of these models, a design vector is defined, which designates what elements that architecture will comprise as well as their parameters. Models of those architecture elements generate values of metrics that correspond to those architecture parameters. This may be done using physics-based models, parametric models, look-up tables based on historical data, etc. Each architecture generated by OPN therefore yields a set of corresponding indicator metrics. The indicator metrics and their corresponding weighting factors are used to create a proximate measure value for that particular architecture. The sum of proximate measure values within a category creates the architecture score within that category. For each category, there is a benchmark value defined by a given mission profile. The scores in all categories generated for each architecture are normalized against those benchmark values to aid in comparison. The normalized scores are depicted in a bar chart like the one shown in Figure 5

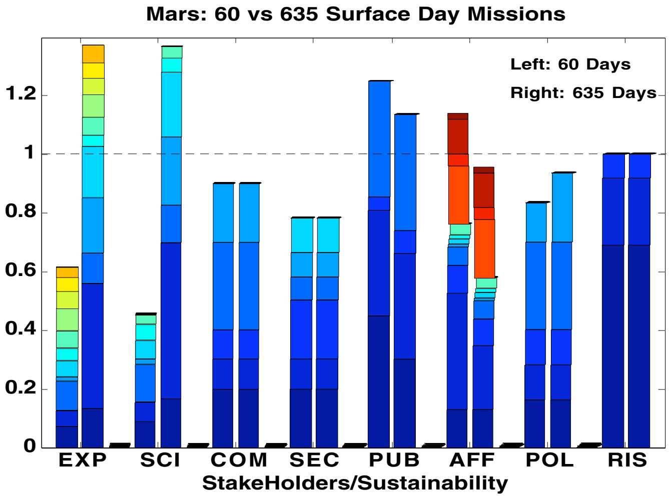

Figure 5. Architectures assessment by metric categories (pillars of sustainability).

Figure 5 compares two architectures for Mars exploration, one that considers a 60 day stay on Mars surface (left) and another one that considers a 635 day stay (right). The categories EXP (exploration value), SCI (science value), COM (commercial value), SEC (security value), PUB (public value), AFF (affordability), POL (policy robustness) and RIS (risk & safety) are presented separately to show readily where the relative strengths and weaknesses of an architecture lie, as well as to aid interpretation of the outcome. For example, in Figure 5, the public value of a long stay mission is lower than of the short stay mission because of the likely higher density of new and high visibility events during the shorter period. The colored small rectangles in each bar of Figure 5 represents the contributions of individual metrics to the architecture score.

It is important to note that this approach produces a *relative assessment of the value* of a given architecture. The scores generated are not absolute values, but ordinal ranked values. Consequently, an architect can determine which of a number of candidate architectures is

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[‡‡] The technical architecture analysis portion of this study proceeded concurrently with the stakeholder value analysis. Because of differing rates of progress in the respective areas of research (more mature areas such as technical architecting proceeded more rapidly than less the mature area of stakeholder analysis), estimated values were used to weight the proximate measures. Preliminary proximate measures weights were used to create those estimates and were generated by the stakeholder value analysis using the following process. The extent to which the proximate measures were an indicator of progress on the exploration objectives was estimated using the same process outlined in Section IV. A team of researchers individually assessed the relationship between exploration objectives and the proximate measures, and then collectively reviewed the ratings to create a matrix with Exploration Objectives arrayed by Proximate Measures. The rating scale was the same 0, 1, 3, 9 scale as described previously, with negative values indicating an opposite correlation. Weighted exploration objectives by societal interest category were created as described in Section IV (and are found in Appendix B.) The multiplication of the weighted exploration objectives by the matrix just described produces weighted proximate measures. In future spirals of this project, the weighting factors will be developed directly from the stakeholder value analysis.

better than the others, but not necessarily by how much. This is useful for filtering through a large architecture trade space to identify the most promising candidates. Once that has been done, more detailed and rigorous analysis must begin to predict more accurately the expected performance of architecture candidates. This initial step is valuable because it helps avoid locally-optimized designs that may perform poorly in a global or extended time-frame context.. This discussion also illustrates how the values of societal stakeholders, seemingly diffuse, can be used to guide analysis and outcomes of a technical system architecture.

B. Enterprise Architecture

The architecture of the exploration enterprise will play an enormous role in enabling the sustainability of the exploration effort. It will fall on the exploration enterprise to define, evolve and operate the exploration elements and to continuously deliver value to the stakeholders. This includes defined roles and responsibilities for each stakeholder to ensure that overarching exploration objectives are pursued, that the exploration campaign strategy is executable, and that critical technologies are available when needed to enable the evolution and expansion of the exploration technical system of systems (SoS.) It requires that the enterprise learn, evolve, and adapt over time and with the expanding SoS. It should build on "Lean Enterprise" architecting principles to create an adaptive enterprise that uses continuous improvement to minimize waste, risk, and cost. It must ensure that the value proposition for all stakeholder participants remains intact over the lifetime of the initiative. The enterprise architecture must provide high-compliance and high-performance operations with consistently expanding capability and minimal operational variance. It is our view that the Exploration Enterprise will be sustainable in large part because it will consistently deliver on its expanding objectives with high reliability and safety.

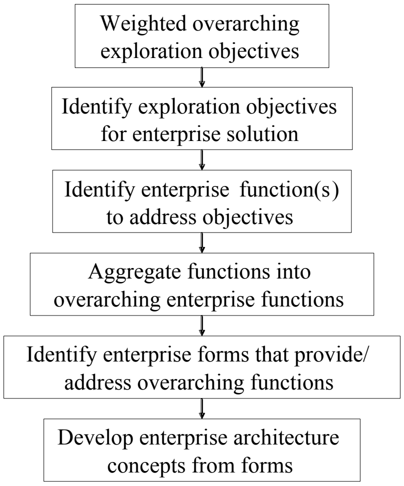

Figure 6. Flow of stakeholder-based metrics into enterprise architecture analysis.

In approach, our process for defining the enterprise architecture is very similar to that for defining the technical architecture. The principle steps are shown in Figure 6. Many exploration objectives (and components of sustainability) can be addressed by multiple approaches, so a first step for enterprise architecting is to identify objectives that will be met primarily (or influenced heavily) through enterprise design and/or operations. Overarching exploration objectives are ranked by whether they can be best accomplished using approaches principally involving enterprise architecture, policy, hardware, or information systems. The subset of objectives identified as best achievable by enterprise architecture became the starting point for an iterative decomposition exercise aimed at linking objectives to specific enterprise attributes and, ultimately, functions.

While still early in the development of this approach, we are already seeing the potential to develop a clearly defined set of enterprise level principles, functions and processes based on stakeholder needs and exploration objectives. With these principles, functions and processes defined, existing research and literature on general management, lean enterprises, and other organizing concepts will provide the material to develop actionable plans, policies and organizational forms and relationships.

C. Policy Development

A robust policy structure is a primary component of space exploration sustainability. The exploration stakeholders most closely associated with policy—the Executive and Legislative branches of the US government—are direct stakeholders that control vital fiscal resources, as well as craft the legislation and directives that define the rules of engagement between the exploration enterprise and the other exploration stakeholders. International partners, while indirect stakeholders to the US space exploration program, also provide critical enabling funding, technology, and personnel. The policy stakeholders are principally government entities, and as such, are also intermediaries between the exploration enterprise and other exploration stakeholders. This means that they simultaneously provide guidance, vision, and enabling resources, but also rely on the support and feedback of other constituent stakeholders as a signal that those stakeholders value the benefits that space exploration activities generate. Policy stakeholders are a key part of the exploration value stream and value delivery system, enable value delivery by directing activities that benefit other stakeholders, and ensure through oversight that correct technical, operational, and strategic objectives are pursued to enable that value delivery. Because of these interdependencies, it is important that policy development for sustainable space exploration be an integral part of the development of the technical and enterprise exploration systems.

The formal approach we are using for policy development as part of this study is to develop functional models of the executive and legislative policy-making and policy–executing processes. This is done by identifying and analyzing relevant legislation, appropriations and authorization language, and executive policy documents, currently for the period from 1995 through 2004. Historical policy documents are also used to provide background information. Content analysis is being used to construct categories of policy action, as well as identify areas of uncertainty or risk for the exploration system. These categories and underlying data will enable the quantification of positive or negative returns from specific courses of action in space exploration, including technical, mission, or enterprise architecture choices. Once the development of the policy process models is complete, they will be cross-referenced to the overarching exploration objectives, technical system of system architecture, and enterprise architecture study activities. For instance, one of the assessment metric areas for technical architecture tradeoffs is policy. Completed policy models will allow, for instance, the direct comparison of specific technical architectures on the basis of their policy robustness (current models rely on heuristics and estimates as placeholders.) This work is currently underway.

VI. Conclusion

This paper presents the first stages in development of a process that is aimed at clearly defining and then architecting a socio-technical system (enterprise and technical system architecture) for a unique public sector activity. Its ultimate goal is to identify sustainable approaches for space exploration. Because of its sustainability focus, the scope of this study has expanded to include not only the technical architecture, but also the general delivery of value to all stakeholders in the space exploration system. This includes considerations of the stakeholder community, its needs and resulting objectives for space exploration, and how those objectives determine choices made for the design of the technical system of systems architecture, the exploration enterprise architecture, and supporting policy environment. Through this work we are integrating a number of existing tools and processes, and also developing new analysis tools and processes, for instance for enterprise analysis and architecting. As part of an ongoing effort, we expect that changes to the methodology and method will be made as experience and knowledge is gained with it. To date, many parts of the analysis have been done with graduate students; for actual application of the method, practicing experts (if not stakeholders and/or their representatives) should at minimum be involved in the development of stakeholder needs and exploration objectives.

The unique approach to this study is generating a number of new and important contributions. First, it elevates sustainability as a primary consideration during exploration system architecting and design. More traditional system architecting would likely focus primarily on achieving the very challenging technical objectives. The 4 components of sustainability bring focus on delivering value to exploration stakeholders over the lifecycle of the endeavor, addressing risk and affordability not only through the technical system, but also through the exploration enterprise, and the policy environment. These additional objectives are forcing the development of new analytical techniques and processes to enable system architecting, systems engineering, and enterprise design and management. We believe these tools and insights will benefit system architects not only for space exploration, but in other complex engineering systems, by providing a more comprehensive set of information with which to make system design and management decisions.

Despite the promise of these new techniques and tools, this is an early report of efforts. There is considerable work yet to do. Areas that show promise, and deserve additional attention include development of multi-stakeholder utility models and theory to enable complex system architecture tradeoffs and optimization; more fully-developed methods for transforming stakeholder objectives to enterprise functions, including specific design and implementation guidelines; and the development of an integrated process for linking policy-making with technical system and enterprise design. These are all areas in which our team is currently working and hope to produce progress updates soon.

Appendix A

Overarching Exploration Objectives (order does not imply priority):

1. To increase knowledge about the evolution of the solar system
2. To pursue sustained exploration by locating and exploring in situ resources
3. To prepare for the exploration of the next destination by increasing operations, resources and infrastructure knowledge
4. To increase crew safety, ensure crew physical health and increase crew comfort

5. To increase and maintain high public interest and awareness
6. To increase and maintain high workforce motivation
7. To promote youth interest for science and engineering
8. To increase and maintain high support to NASA
9. To interact with explorers
10. To produce high quality transmitted data
11. To reduce entry barriers for businesses needing access to orbit by developing market for launch services
12. To promote technologies of dual use: commercial space, defense-space and other agencies—space.
13. To promote technology development
14. To promote participation of or organizations outside NASA in space science, engineering and development
15. To reduce cost per module by promoting University participation in development, increase in production volume and partnerships with other Nations
16. To increase likelihood of technology availability by assuring technology roadmap overlap with international partners
17. To assure a continuous and steady pace of exploration by phased development
18. To promote sense of US leadership in the international arena
19. To enhance planetary protection from extraterrestrial threats
20. To assure no other nation can claim sovereignty of celestial bodies
21. To stimulate economic growth by investing in technology development
22. To assure continued political support for space exploration by demonstrating government effectiveness
23. To assure continued political support for space exploration by consistently executing to fiscal and operational objectives
24. To enable space exploration by reducing policy and legislative barriers

Appendix B

	STAKEHOLDER CLASSES				
OBJECTIVES	Exploration	Science	Economic	Security	Public
To increase knowledge about the evolution of the solar system	2.3	4.3	0.7	4.5	2.7
To pursue sustained exploration by locating and exploring in situ resources	7.0	4.0	2.0	1.5	2.7
To prepare for the exploration of the next destination by increasing operations, resources and infrastructure knowledge	9.0	4.0	4.0	0.5	2.7
To increase crew safety, ensure crew physical health and increase crew comfort	7.0	4.0	1.3	3.0	5.0
To increase and maintain high public interest and awareness	5.0	4.0	2.0	4.5	6.5
To increase and maintain high workforce motivation	7.0	4.3	6.3	3.0	4.2
To promote youth interest for science and engineering	4.3	4.3	5.0	5.0	3.0
To increase and maintain high support to NASA	7.0	4.0	1.3	1.5	3.2
To interact with explorers	3.7	1.3	0.3	1.5	5.0
To produce high quality transmitted data	7.0	4.3	3.3	6.0	4.3
To reduce entry barriers for businesses needing access to orbit by developing market for launch services	6.3	2.3	7.0	6.0	3.7
To promote technologies of dual use: commercial space, defense-space and other agencies - space.	3.7	2.3	5.0	3.0	2.5
To promote technology development	3.7	2.3	5.0	3.0	1.7
To promote participation of or organizations outside NASA in space science, engineering and development	4.0	3.3	4.3	6.0	1.0
To reduce cost per module by promoting University participation in development, increase in production volume and partnerships with other Nations	2.3	3.7	2.3	6.0	2.0
To increase likelihood of technology availability by assuring technology roadmap overlap with international partners	3.0	2.3	1.7	4.5	1.8
To assure a continuous and steady pace of exploration by phased development	9.0	6.0	4.0	4.5	4.0
To promote sense of US leadership in the international arena	1.7	1.0	1.7	0.5	3.8
To enhance planetary protection from extraterrestrial threats	1.7	1.3	0.3	2.0	0.8
To assure no other nation can claim sovereignty of celestial bodies	1.3	0.3	0.3	1.5	1.7
To stimulate economic growth by investing in technology development	3.7	1.0	6.3	2.0	4.3
To assure continued political support for space exploration by demonstrating government effectiveness	7.0	4.3	1.7	1.0	5.0
To assure continued political support for space exploration by consistently executing to fiscal and operational objectives	4.3	3.3	0.7	1.5	5.0
To enable space exploration by reducing policy and legislative barriers	7.0	4.0	2.0	0.5	2.8

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