Preliminary Report: A Study of Options for Future Exploration of Mars

Mars Exploration Strategy 2009 – 2020

WHITE PAPER

by

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PREFACE

NASA is currently pursuing an aggressive, science-driven agenda of robotic exploration of Mars, with the aim of concluding the current decade of research with the first landed analytical laboratory on the martian surface since the Viking missions of the 1970's. This mobile science laboratory will propel Mars exploration into the next decade for which the search for evidence of biological activity is the ultimate goal. For the past year, an intensive effort has been underway to look beyond the current decade toward future investigations that lead to discovery. This effort involved the synthesis of many, alternate lines of scientific enquiry together with programmatic and scientific decision criteria. These investigation pathways were then linked with methods tailored to identifying gaps in our current technological investments that must be filled if future exploration is to be pursued cost-effectively. This document describes the planning processes used to achieve, and the outcome of, the synthesis that culminate in a strategy for the intensified scientific exploration of Mars in the time period from 2009 to 2020. The foundation of the strategy is that next decade exploration will build upon the new knowledge gained in this decade. Planning the future, while embracing the fact that unknown and unpredictable discoveries should determine the course of research, has been accomplished by creating explicit alternate *Pathways* of exploration. Each *Pathway* included in this strategic plan comprises a specific sequence of robotic missions required to accomplish it by means of targeted measurements. In addition, NASA, cognizant of the uncertainty inherent in exploration, views this document to be "living". The task here has not been to foresee the future, but to enable it.

INTRODUCTION

NASA's goals for its Mars Exploration Program currently emphasize the search for ancient and modern habitats on Mars, as well as the overarching objective of discovering how planets evolve into habitable worlds. This document presents an exploration strategy aimed at advancing these goals using science-driven robotic missions, on and near the surface as well as from orbit. This strategy builds upon the enormous advance in knowledge gained from robotic investigations conducted in the current phase of the study of Mars (1996 through 2003) and charts the course of exploration in the *Next Decade* (2009 through 2020).

The strategic plan for *Next Decade* of exploration arises from a collaboration of members of the Mars science community together with advanced mission planners from JPL, technologists, and senior members of NASA's Mars Exploration Program (MEP). Chartered as an *ad hoc* working group, the Mars Science Program Synthesis Group (MSPSG) was tasked by NASA Headquarters with synthesizing a broad range of planning guidance formulated by the science and engineering communities, including explicit priorities for investigations. Science priorities were coupled with studies of the technical and fiscal feasibility of missions needed to conduct the high priority measurements. The resulting plan offers a limited set of decision criteria that allow alternative investigation options to be selected and pursued, depending upon the findings of research in the present decade of exploration.

ENGAGING THE SCIENCE COMMUNITY IN THE PLANNING PROCESS

The Mars Exploration Program leadership has consistently encouraged the science community to engage in and suggest strategies for conducting Mars scientific exploration. In response, the Mars science community utilized the platform of their longstanding organization, the Mars Exploration Program Analysis Group (MEPAG), to build community consensus on investigation strategies for Mars in the *Next Decade* and to articulate those strategies to NASA. MEPAG is an informal community-based and led organization of approximately 100 scientists who represent collectively the Mars science community nationally and internationally. Earlier interactions between MEP/NASA and MEPAG resulted in the development of key attributes and science direction of the program of exploration being pursued at Mars today. During 2000, the MEPAG produced a highly regarded document (Greeley, 2001, JPL Publication 01-7) that describes and prioritizes science objectives, investigations, and measurements that emanate from NASA's overarching goals for Mars exploration. Indeed, the MEPAG hierarchical treatment of scientific priorities for Mars exploration has been used by the National Academy of Sciences recently as the basis for discussion when assessing the current state of Mars exploration.

Building upon the earlier consensus-built science priorities, MEPAG contributed its views on *Next Decade* exploration. Specifically, MEPAG established subgroups of scientific experts to work directly with advanced mission planners from JPL and industry to formulate a suggested future strategy for exploration. In parallel, formal advisory groups to NASA – the Space Science Enterprise Advisory Committee (and its Subcommittee for Solar System Exploration) and the National Research Council – formulated recommendations for areas of research emphasis, as well as missions for Mars for the period from 2002 through 2013. The advice of these committees played a central role in the MEP planning process, as did the suggestions and investigation priority findings contributed by MEPAG.

GUIDING PRINCIPLES FOR PLANNING *NEXT DECADE* EXPLORATION

MEP leadership initiated their planning process by establishing terms of reference for MEPAG's contributions to *Next Decade* planning. These principles provided a common understanding of the purpose and direction of the planning effort. Included were the following fundamental principles upon which NASA's scientific exploration of Mars rests:

- Mars exploration will be scientifically balanced to the maximum extent feasible within resource constraints.
- The overarching objectives for MEP are: **Life**, **Climate**, **Geology**, and **Preparation for Human Exploration**. First among these objectives of nearly equal priority is Life.

MEP also provided additional programmatic guidance to MEPAG.

- The scientific prioritized objectives of Astrobiology are to be emphasized *Next Decade*.
- Plans for *Next Decade* investigations must retain sufficient flexibility to enable the program to respond to discoveries made in this decade.
- For *Next Decade* planning, not one but several options for scientific investigation are required.
- At least one of the options should **not** include the high science priority, but presumed high cost and risk Mars Sample Return (MSR) mission before 2020.
- Consideration should be given to whether a lower-cost, scientifically- productive MSR is feasible in at least one of the options.

Investigation *Pathways*

Scientists were advised that MEP had created a framework for planning in which to cast the required multiple options for investigations and the associated missions to conduct them. Within this framework, hereafter referred to as investigation *Pathways*, alternative lines of investigation can be conceived, each responding to different scientific hypotheses for how Mars works, planned in detail, and associated with missions to Mars that would be needed to implement the measurements they require.

Adopting the *Pathways* approach diverse groups of scientists conceived and evaluated many options for *Next Decade* exploration. In the main, these alternative concepts depended on measurements of rock, soil, ice, and atmosphere to be made by *in situ* instruments. Most lines of investigation suggested also utilized the detailed and definitive measurements of martian samples that can be accomplished only by state-of-the-art analytical instruments in Earth laboratories. Landers and rovers would carry *in situ* instruments, most of which have not flown previously in space, to sites where liquid water would be determined, from investigations performed this decade, to have persisted on the martian surface at some time in the past. Similarly, samples collected and returned to Earth would be collected from ancient sites that show compelling evidence of persistent liquid water; for, it is argued by similarity to Earth, liquid water and the associated climatic conditions that it implies provides the environment suitable for the origin and survival of life.

Analysis and discussion within and among the science groups continued until MEPAG delivered to MEP a consensus proposal for exploring Mars in the *Next Decade*. The MEPAG vision includes four *Pathways* in which each path arises from testable scientific hypotheses. At the direction of MEP, no specific flight missions were defined by MEPAG. Along with their thoughtful plan, several specific findings were presented relating to the desired pace of the search for habitable environments on Mars. Of particular importance to the program is a finding by MEPAG suggesting that a new, more cost-effective, robotic concept for returning samples of Mars to Earth was feasible.

Early sample return from Mars

The planetary science community continues to rank Mars Sample Return (MSR) in the category given highest priority for a *Next Decade* Mars missions. Because of the significant limitations of scientific instruments that can be flown on spacecraft (as well as enormous constraints on *in situ* sample preparation and processing), some of the most critical measurements required in all *Pathways* ultimately depend on those measurements being made in Earth laboratories on returned samples.

The emphasis on MSR is not new. Many science groups over the past three decades, including science groups that provide formal advice to NASA on its program of solar system science, give MSR exceptionally high priority, e.g. the National Academy of Science Committee for Planetary and Lunar Exploration (COMPLEX). However, in recent years it has become evident to the science community that resource constraints and a paucity of flight-proven hardware required for MSR argue strongly in favor of an MSR mission of greatly reduced scope – compared with the current ambitious mission concept (i.e., an MSR with a mobile sample collection system). In response, a new mission concept, the Ground Breaking MSR, was developed by MEPAG through collaborations with JPL advanced mission engineers and competitively selected industry contractors. Ground Breaking MSR, which foregoes the original rover-based sample collection scheme, was judged by MEPAG to be a necessary compromise between science and budget that could obtain samples of martian soil (with included lithic fragments) and atmosphere early in the *Next Decade.* This Ground Breaking MSR would consist of a simple lander whose only tools would be an extendable arm carrying very simple sampling devices (e.g. a combination of a scoop and sieve and a miniature rock corer). The absence of mobility in the Ground Breaking MSR is acceptable only because the mission would visit a site that has been previously characterized as exceptionally interesting by earlier *Pathway*-derived landed or orbital missions. Precision landing of the vehicle would ensure that the requisite site is reached. This static lander-based sampling system would produce unparalleled insight into the state and evolution of Mars by virtue of its access to materials at a site of known (via prior reconnaissance) scientific importance. However, MEPAG also found that the success of Ground Breaking MSR would not diminish the critical scientific need for a future MSR with a Rover to gain access to diverse samples and water-lain deposits on the martian surface.

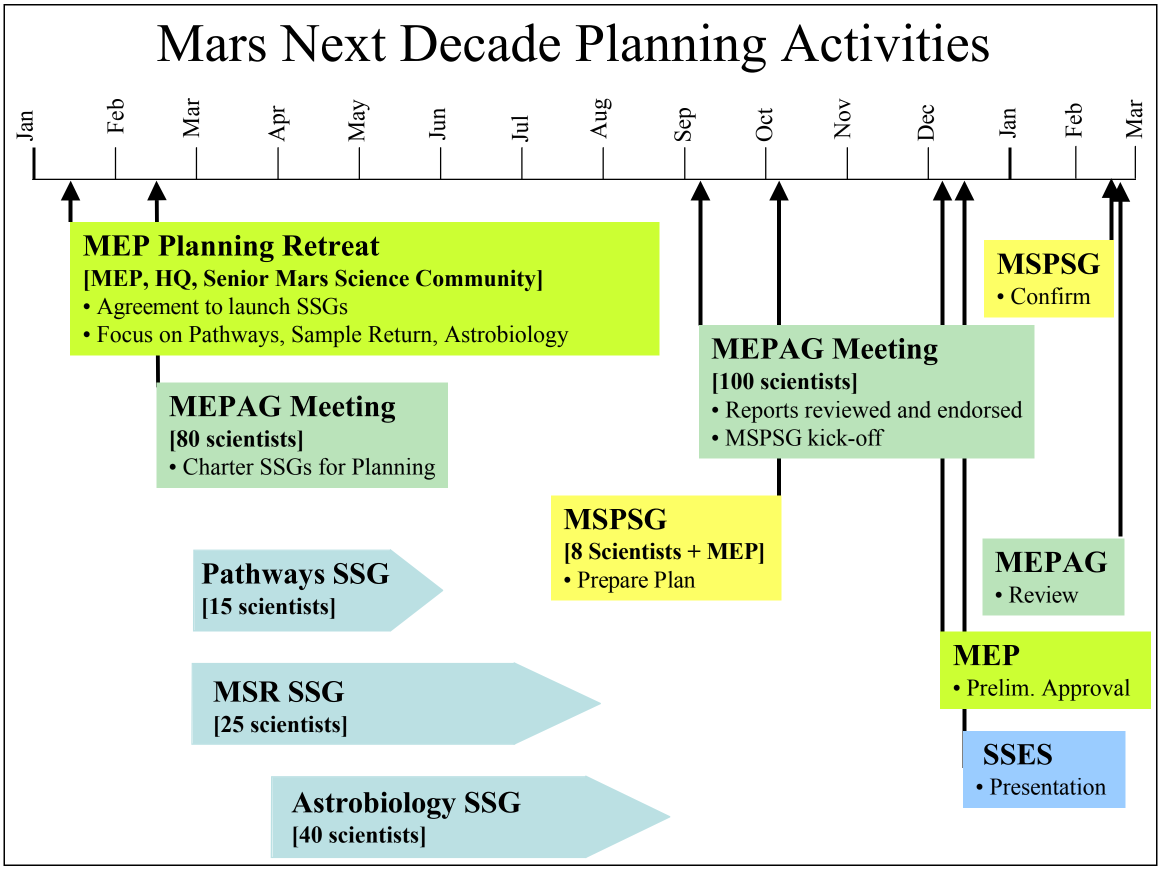

Figure 1. Activities Contributing to Strategic Plan

SYNTHESIS OF SCIENCE, ENGINEERING, AND TECHNOLOGY

MEP moved to integrate the multiple sources of science input into potential strategies and to assess the engineering and programmatic feasibility of those strategies (see the schedule of planning events in Figure 1 above). The team of scientists, engineers, and senior program leadership, known as MSPSG, was chartered by MEP with integrating the diverse inputs, suggestions, and plans from MEPAG and the formal NASA science advisory groups, e.g. the recently published NRC Solar System Decadal Survey and the COMPLEX Mars Program Assessment Report. Equally vital to MEP's planning process was the MSPSG's task of formulating the architecture for the Mars Exploration Program for *Next Decade* that will address the priority science objectives within the anticipated boundaries of technical practicality and fiscal resources.

MARS EXPLORATION *PATHWAYS* FOR 2009 – 2020

The strategic plan that emerged from the 2002 process includes four *Pathways* from which program leadership, supported by concurrent scientific advice, can select. Selection of a specific *Pathway* will depend on many factors, programmatic as well as technical, and will reflect the accumulated knowledge of Mars at the time of a decision. Each *Pathway* is self-consistent and supported by a specified series of missions together with science payloads capable of achieving the high-priority science objectives that best follow-up discoveries by precursor missions. Considerable care has been taken in the overall strategic plan to create *Pathway* mission sequences that are consistent with best available forecasts of the MEP budget in the *Next Decade*. Nevertheless, such forecasts are unavoidably very approximate. Although the future budget is uncertain, program forecasts do serve to provide useful scaling for *Pathways* and the missions they contain, i.e. the four *Pathways* are approximately equal in cost. The *Pathways* are, therefore, supportable by similar budgets and annual budget profiles. The fiscal implications of pre-mission technology development; mission, spacecraft, and instrument development; launch costs; mission operations; and science data analysis are all included in the cost estimations for each *Pathway*.

It is important to emphasize that, once a Pathway is initiated, MEP is not compelled to continue along it if it is determined to be less scientifically productive than another – switching to one of the other paths is always an option, although a response time of some years is unavoidable given time inherent in the development of technology and the building of spacecraft. *The MSPSG noted that technology is one of the clear beneficiaries of Pathway formulation. Technology development can be planned to maximize the flexibility of the Mars program, as well as to emphasize technologies that are common to missions among multiple Pathways.*

The four investigation *Pathways* comprising the strategic plan are in Figure 2, below, together with the motivating "line of scientific enquiry" for each.

Mars Exploration *Pathways*, 2009 - 2020

Pathway	**Lines of Scientific Enquiry**
Search for Evidence of Past Life	• Science from First Decade missions plus Ground Breaking Sample Return confirms ancient Mars was wet and warm – Locating and analyzing water-lain sedimentary rock is primary goal – Pathway includes search for evidence of past life
Explore Hydrothermal Habitats	• Exploration in First Decade discovers hydrothermal deposits (active or fossil) – Probability of hydrothermal regions being discovered is potentially high – Hydrothermal habitats are focus of second decade of Mars exploration – Potential for discovery of evidence of past and present life is greatly improved
Search for Present Life	• Commits to search for present life at sites determined to be modern habitats by First Decade missions – Search for life at active hydrothermal deposits or polar caps. – Path would be taken only following a revolution in programmatic/Executive Branch interest in Mars. – MSR with mobility is included as only reliable, validatible means of detecting of life.
Explore Evolution of Mars	• Science of First Decade determines that Mars was never globally wet – Determine the loss mechanisms and sinks for water and CO_2 over time. – The terrestrial planets evolved very differently, much more so than we had thought. Why? – Were the initial conditions on Venus, Earth and Mars similar or very different?

Figure 2. Lines of Scientific Enquiry are *Pathways* for Mars Exploration

Scientific Motivations for Mars Exploration *Pathways*

Search for Evidence of Past Life

The *Search for Evidence of Past Life Pathway* executes a search for evidence that points to the possible existence past life on Mars. On ancient Mars, environmental conditions (or climate) may have been favorable to origin and survival of life. The search for biosignatures motivates the line of scientific enquiry of this *Pathway*. The path of Mars exploration in the current decade places high priority on identifying sites, such as sedimentary deposits that show evidence of either deposition or alteration by liquid water in the past where microbial life is found Earth. The task of the *Search for Evidence of Past Life* will be to examine those sites identified as having the highest potential for revealing evidence of past life. The analytical and sample acquisition tools needed to carry out this research will be continuously improved as the sequence of missions is implemented. The pivotal measurements for the *Search for Evidence of Past Life Pathway* will be made by the Mars Reconnaissance Orbiter (MRO) and the Mars Science Laboratory (MSL). MRO focuses on the planet-wide search for evidence of persistent liquid water on the surface in the distant past. This evidence will be critical to sustaining our current view that the martian surface was once habitable. MRO will also identify the most scientifically productive landing sites for future rovers, landers, and sample return missions in this and other *Pathways,* including MSL. MSL will investigate the carbon chemistry in near surface rocks and soil and provide a rigorous and definitive examination of their mineralogy as well as the extent to which they were formed or altered by water. Later missions in this *Pathway* will build upon this foundation of investigations and provide much more definitive tests for evidence of past life than will be possible from MSL and earlier landed missions. Advanced *in situ* instruments are expected to conduct bio-molecular chemical analysis and higher spatial resolution examination of samples. The technology to acquire difficult-to-access samples, such as those buried several to tens of meters below the surface, will also be developed.

This *Pathway* increases systematically our ability to discover potential past habitats of simple microbial life, their biosignatures, and perhaps direct and definitive evidence of past life. Key to the full realization of this *Pathway* will be an astrobiology-focused rover-based investigation late in the *Next Decade* that provides greatly improved access to water-lain sedimentary rock samples, either through deep-drilling or long-traverses for detailed searches for past life. Present expectations are that the *Search for Evidence of Past Life Pathway* will provide a strong motivation for future rover-based sample return missions beyond the *Next Decade* to sites determined, during the conduct of the *Pathway*, to be most significant.

Explore Hydrothermal Habitats

Hydrothermal activity on Mars may have provided an energy source (i.e., water, heat, nutrients) for the evolution of life. Hydrothermal activity in the past leaves behind deposits that are also deemed likely to preserve evidence indicative of habitats, evidence of biogenic elements (i.e., C, H, N, O, P, S) and prebiotic compounds, as well as preserving microbial signatures. Although there is good reason to suspect that active or fossil hydrothermal deposits exist on Mars, none have been identified to date. Further, the mineralogy and isotope geochemistry of SNC (Martian) meteorites suggest that earlier Mars may have had low temperature aqueous and/or hydrothermal conditions that alter their host rocks (e.g., carbonates and sulfides in ALH84001 and other martian meteorites). Consequently, the potential for discovering hydrothermal deposits by means of remote sensing is reasonably high, especially in the current decade. Should an active vent be discovered, the possibility exists that such a vent would be an abode of life. The *Explore Hydrothermal Habitats Pathway* is, necessarily, discovery driven.

Orbital observations from Mars Odyssey and Mars Reconnaissance Orbiter (2005) may reveal that there are active or ancient hydrothermal sites (i.e., associated with volcanism or impact melt sheets). Results from Mars Odyssey also suggest global-scale subsurface deposits of water ice that could have important implications where found in close proximity to thermal sources. If active or ancient hydrothermal vents or deposits are found, this *Explore Hydrothermal Habitats Pathway* will focus, specifically, on investigating the origin and evolution of one or more of those sites, including their geologic settings in context. Landing the 2009 MSL mission at the hydrothermal site will be a critical step in initiating this *Pathway*. The mineralogy, composition and redox potential of the associated hydrothermal vent deposits will have very high priority for MSL. A search for biosignatures (organic compounds, isotopic signatures, and microscopic textural indicators) and extinct and/or extant life will be a next step in this *Pathway*.

<u>Search for Present Life</u>
The *Search for Present Life Pathway* follows upon the discovery, by earlier orbiting or landed missions, that environments on present Mars have the potential to support life. Habitats may include the near subsurface, active hydrothermal systems, or source regions of high-latitude gullies recently detected by MGS. The subsurface environment is particularly interesting in that it is protected from harsh surface conditions on Mars and may provide a relatively warm water-rich environment.

The mission objectives of the *Search for Present Life Pathway* are to access regions of present groundwater, hydrothermal flow, or substantial near-surface water ice reservoirs. The layers of ice and dust in the polar environment -- and revealed by Mars Odyssey to also exist at lower-latitudes -- have increasingly come to be viewed as a potential habitat for microbial ecosystems, possibly analogous to those existing in terrestrial permafrost. The measurement approach is to examine the habitat for signs of organic carbon compounds, the chemical composition of the water and ice, including pH and redox potential (and search for any reduced Carbon), as well as a careful study of local geology to determine whether water is now exposed at the surface. This *Pathway* will feature a strong emphasis on *in situ* life detection, more complex sample access problems, and require a very substantial near-term technology investment in instruments and spacecraft cleanliness for the purposes of planetary protection and the avoidance of false-positive detections. It is clear that a suggestion by *in situ* measurements of present life will necessitate confirmation in Earth's laboratories through measurements of returned samples.

<u>Explore the Evolution of Mars</u>
Explore the Evolution of Mars Pathway will be initiated following the discovery, possibly prior to the start of *Next Decade,* that the currently favored hypotheses for the climatic history of Mars are incorrect. For example, ongoing and future investigations (e.g., MER rovers, MRO) may show that there remains no convincing evidence of wet conditions on ancient Mars involving standing bodies of water, as has thus far been interpreted from orbital remote sensing to date. In this case, the program's current focus on the search for surface habitats would be given a significantly lower priority – unless, of course, liquid water is found on or near the surface of Mars today. With this surprising discovery would come the attendant mystery of how the terrestrial planets evolved so very differently, given their gross similarity? The *Explore the Evolution of Mars Pathway* would then focus on the distinct characteristics of Earth's evolution and how it arose, particularly by contrast with those of martian history, as determined by targeted measurements from specific missions. Understanding the evolution of Mars, from its interior (core) to the top of its atmosphere, would be a derived requirement of this *Pathway.*

The Missions that Implement the *Pathways*
In creating this plan for exploration, MSPSG, working with mission-design and systems engineers, devised missions and mission sequences for each of the above *Pathways*. The content and character of each mission was dictated by science objectives (and associated prioritized

measurements), the sequence and plausibility of advances in technology, and the anticipated growth in our understanding of Mars, as well as our experience in operating on its surface. In every case science requirements determine spacecraft functionality – feed-forward of technical capabilities to future missions was also a consideration. Details of functionality were identified for three categories of spacecraft: Rovers and Landers; Orbiters; and Sample Return (i.e., characteristics common among mission types were also specified). The architecture of the Mars Exploration Program for *Next Decade* is shown below in Figure 3.

Mars Exploration *Pathways* Missions

Pathway	**2009**	**2011**	**2013**	**2016**	**2018**	**2020**	**NOTES**
Search for Evidence of Past Life	**MSL to Low Lat.**	Scout	**Ground Breaking MSR**	Scout	**Astrobio. Field Lab or Deep Drill**	Scout	**All core missions to mid-latitudes. Mission in '18 driven by MSL results and budget.**
Explore Hydrothermal Habitats	**MSL to Hydrothermal Deposit**	Scout	**Astrobiology Field Laboratory**	Scout	**Deep Drill**	Scout	**All core missions sent to active or extinct hydrothermal deposits.**
Search for Present Life	**MSL to N. Pole or Active Vent**	Scout	Scout	**MSR with Rover**	Scout	**Deep Drill**	**Missions to modern habitat. Path has highest risk.**
Explore Evolution of Mars	**MSL To Low Lat.**	Scout	**Ground Breaking MSR**	**Aero-nomy**	**Network**	Scout	**Path rests on proof that Mars was never wet.**

Figure 3. Missions that Comprise *Pathways* of Mars Exploration

Science objectives and the approaches to implementation adopted for the missions comprising the four *Pathways* are briefly described in the Table below.

Mars Exploration *Pathway* Missions
2009 – 2020

Mars Science Laboratory (MSL)
Depending on the *Pathway* MSL would investigate potential habitats, e.g. water-lain sedimentary rocks or a hydrothermal deposit (active or fossil) and study the geochemistry and mineralogy of the site in detail. If earlier missions suggest that Mars was never globally wet, MSL would focus on exploring departures in the evolution of the terrestrial planets on the basis of *in situ* analytical tools.

Aeronomy Mission
A small orbiter, Scout-class, would carry both *in situ* and remote sensing investigations focused on understanding the upper atmosphere and mechanisms of atmospheric escape.

Astrobiology Field Laboratory
This mission would land on and explore a site thought to be a habitat. Examples of such sites are an active or extinct hydrothermal deposit or a site confirmed by MSL to be of high astrobiological interest, such as a lake or marine deposits or a specific polar site. The investigations would be designed to explore the site and to search for evidence of past or present life. The mission will require a rover with "go to" capability to gather "fresh" samples for a variety of detailed *in situ* analyses appropriate to the site. *In situ* life detection would be required in many cases.

Deep Drill
Otherwise similar to the Astrobiology Field Laboratory, the Deep Drill mission would focus on vertical rather than horizontal mobility. A 3m to 10m drill would replace the rover as the primary sample-gathering tool.

Ground Breaking Mars Sample Return (GBMSR)
The GBMSR mission collects samples from the martian surface and returns them to Earth. It is termed "Groundbreaking" because, while maintaining a scientifically valuable mission, the concept is simpler and more affordable than the more sophisticated sample return mission that includes a mobile sample collecting system. GBMSR consists of two identical landers, each of which carries an extendable arm with very simple sampling devices and a context camera. The landers are each supported by an orbiter that returns the collected samples to Earth. The mission is designed to collect a minimum of 500g of fines + rock fragments + atmosphere. Each lander is precision-targeted to sites of known relevant to the "habitability" goals of the program.

Mars Sample Return (MSR) with Rover
The MSR with Rover consists of a single lander/rover and a return orbiter. The rover is of the Mars Exploration Rover 2003 class but has the capability to collect small rock cores to be included in the returned samples.

Network Mission
A global network of ten or more long-lived fixed-landers focused on seismology and geochemistry measurements at distributed sites, as well as meteorological monitoring.

Mars Scouts
Competitive Scout missions address fundamental scientific questions about Mars and provide the ability to follow-up on recent discoveries from earlier missions. The selection of these small missions, proposed to a NASA competition by scientists, is based upon scientific merit and to the degree to which the mission addresses the science goals of the Mars Exploration Program.

The Mars Science Laboratory 2009 Initiates the *Next Decade Pathways*

MSL occupies a unique place in Mars exploration because it both concludes the currently planned missions and it initiates the paths of exploration in the *Next Decade*. MSPSG has argued very strongly that MSL will be most beneficial to *Next Decade* exploration, whatever the *Pathway*, if it is designed so that it can respond to knowledge gained from the investigations of the Mars Exploration Rovers 2003 and the Mars Reconnaissance Orbiter 2005. MSPSG went still further by noting that the schedule of exploration embodied by the *Pathways* is dependent on MSL being responsive to the findings of both the MER and MRO missions.

Thus, MSL will be most valuable to Mars exploration if it is adaptable in these areas:

- Preserving access to, at least, 60°S to 60°N latitude and to altitudes up to +2.5 km.
- Sample processing methodology capable of handling not only soil and rock, but also ice-bearing samples.

The dependence of *Next Decade* investigations on the results of MSL leads to the following critical questions regarding the engineering design of the MSL mission:

- Is it feasible for a single design to operate at both high and low latitudes?
- What are the planetary protection implications of an MSL mission landed at high latitudes (i.e., near 60° N or 60°S) and will planetary protection requirements differ significantly for high and low latitude missions?
- Related to the viability of follow-on missions, to what extent will MSL engineering developments feed-forward to future missions, thereby reducing future risk and cost?

Pathways Responding to Discoveries

The adaptability desired of MSL, described above, is a characteristic that is valuable in all *Pathway* missions. The figure below illustrates how the scientific results of early missions guide the content of future missions. This influence has already been illustrated very clearly by the impact of Mars Global Surveyor '96 on the missions to be flown in the current decade. Specifically, MEP was driven by MGS science results to alter the 1996-2007 mission set. The Mars Exploration Rovers and Mars Reconnaissance Orbiter were added to the Mars exploration plan based specifically on the results of MGS. Figure 4 shows explicitly the anticipated influence of missions to be flown this decade on missio*n*s and the *Pathways* they will feed in the *Next Decade*.

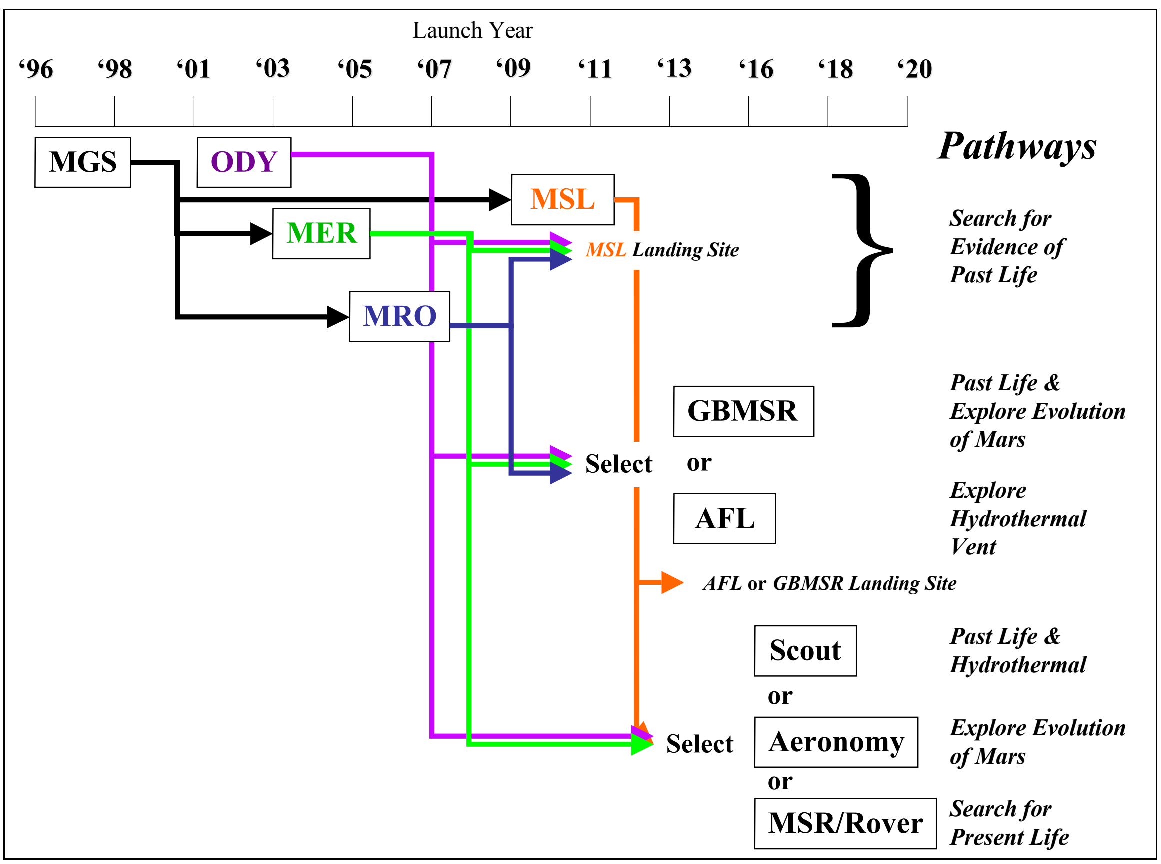

Figure 4. Missions this Decade Determine Future Missions and Pathways

The Decision Process for Selecting Among *Pathways*

Mars exploration, then, depends critically on informed decision making by MEP leadership. Information leading to understanding drives the choice of investigation *Pathways.* Therefore, it is essential that MEP have a methodology for assimilating into its decision process rapidly increasing scientific knowledge, the state of technology readiness, and programmatic direction from multiple sources.

Selection of the appropriate *Pathway* among the four presented here is rendered possible by the most fundamental principle of the strategy – hypothesis-driven exploration. The hypotheses that motivated this program of exploration are testable using the results from missions comprising the program. This is best illustrated by examining Figure 5 (below) in which hypotheses are tested by knowledge gained by missions of this decade and which, in turn, drives the choice of *Pathways.* The timing of MEP decisions is dictated by the duration of spacecraft development, as well as technology investment strategies for the missions launched between 1996 through 2007.

Current Missions '96 - '05

Hypotheses	MGS	Odyssey	MER	MRO	Future Pathways
Persistent Water on Ancient Mars?	✓ YES	✓ YES	Positive	Positive	Search for Evidence of Past Life
			Negative	Negative	Explore Evolution of Mars
Recent Liquid Water?	✓ ?			Positive	Search for Present Life
Hydro-thermal Deposit?		✓ NO		Positive	Explore Hydrothermal Habitats

KEY: (✓) measurements made; (YES/NO) results of measurements; (?) results uncertain; (Pos./Neg.) potential result.

Figure 5. Test Hypotheses to Select Future *Pathway*

Functionality Required in Future Missions

The plan for *Next Decade* exploration was aided by information gleaned from the detailed specification of MSL functionality. A subgroup of MSPSG (the MSL Project Science Integration Group, PSIG) participated in the scientific definition of MSL. The observations for this subgroup have important implications for a number of the *Pathway* missions and are summarized below.

<u>Mobile Access to Localized Sites on the Martian Surface</u>

The science goals of several of the *Pathway* missions depend upon accessing multiple sites near the landing sites. Access is needed to acquire highly diverse samples of rock (and soil) and to traverse and acquire samples from specific terrains, e.g. sedimentary deposits. However, studies of the science requirements of MSL show that it is unlikely that samples will need to be collected from extremely localized targets, such as a very small locale (i.e., at 10 to 100m scales) that is unique. Previously, potential capability discussed for MSL was a rover that could “Go To” targets – a rover traveling from a specific “touchdown” site to a highly localized target many kilometers distant from the site of landing, perhaps previously identified by orbital reconnaissance. This is now seen to be unnecessary for MSL and unlikely to be needed in the *Next Decade* missions.

Development of Advanced *In situ* Instruments
Continued development of *in situ* instruments will be required to support *Next Decade* missions – accelerated if possible. This is a finding by the PSIG arises from the group’s in-depth survey of instrument development activities worldwide.

Preparation of Diverse Materials for *In Situ* Analysis
Requirements for sample preparation for high- and low-latitude missions differ fundamentally by the need at high latitudes for processing ice-bearing samples. Such differing requirements may reduce or eliminate the flexibility needed to support a delayed selection of the MSL landing latitude until late this decade, therefore reducing the program’s flexibility to use information collected by MRO in selecting Pathways late this decade. Resolution of this issue for MSL may restrict the range of options for future paths of exploration.

Importance of Technology Development and Demonstration
Plans for *Next Decade* necessarily make assumptions about specific systems and technologies being demonstrated by precursor missions, particularly missions flown in the current decade. A mission that illustrates important “feed-forward” to later missions is MSL. MSL has important contributions to make in reducing cost and risk for sample return missions, in particular. Included in MSR, both in the Ground Breaking and Rover options, are large mass landed-platforms, entry-descent-landing systems, and hazard detection and avoidance capabilities. Attention needs to be given to downstream missions during the design of MSL and other missions early in the *Pathways*.

ATTRIBUTES OF FUTURE MARS EXPLORATION AND CONCLUSIONS

The challenge of developing a long-term plan that incorporates the voices of many diverse groups has been met through a yearlong process of community input, working group meetings including scientists and engineers, and concluding with synthesis. Critical to the process was the early recognition that no single line of investigation can weather the uncertainties inherent in an endeavor, such as scientific exploration, that is so dependent upon future discoveries. A robust plan of exploration must incorporate alternative paths, as well as the flexibility to adapt and change course. This is particularly true for Mars exploration in which the goal is the exceedingly difficult task of finding habitats beyond Earth.

Some of the following observations made while planning future exploration may have value as NASA considers its options:

- The choice of the most effective line of investigation will depend *strongly* on knowledge gained from the missions flown in this decade: MGS, Odyssey, MER and MRO.

- The science performed by the 2009 Mars Science Laboratory will have an enormous impact on the timing and sequence of future expeditions to Mars (i.e., whether robotic or human-based).
- MSL will most benefit *Next Decade* exploration if the mission has the capacity to respond to discoveries made by the current decade's missions.
- Sample return continues to rank in the category of highest priority *Next Decade* missions.
    - Resources constraints and an absence of proven hardware argue in favor of a first MSR mission that has reduced scope.
    - A new concept for MSR, specifically the Ground Breaking MSR, developed in this planning effort, is judged by the Mars science community to be a necessary compromise in order to obtain samples early *Next Decade*.
    - Success of the Ground Breaking MSR does not diminish the critical scientific need for a future MSR that includes modest in order to ensure access to diverse samples and sedimentary deposits at a site known to be scientifically compelling.
- Mars Scout missions play a very important role in balancing the Mars program among the many science disciplines that contribute to understand the planet Mars and its relation to Earth.
- Investigations to be performed *in situ* depend critically on continued advancements in instrument development.