ON July 20, 1989, then-President Bush called for an effort to return to the Moon and conduct an expedition to Mars, a program subsequently named the Space Exploration Initiative (SEI). The quest for knowledge is a driving force for sending people beyond low Earth orbit; thus science, although not SEI's specific purpose, is an integral part of this initiative. Increasing the effectiveness of the SEI science program is a continuing challenge for mission planners.

Many mission scenarios, or architectures, will have been considered, discarded, and reworked before the optimum plan is selected. Architectures will be chosen based on factors such as cost, safety, schedule, feasibility, and overall ability to accomplish mission objectives. One important criterion is how well an architecture enables us to execute a science program. How we make these choices may mean the difference between an exciting program rich with advancement, intrigue, and surprising discoveries, or a lackluster, disappointing one of little value to the scientific community.

Different architectures create different opportunities for science. The collective return or value of a science program defies simple appraisal. Unlike most engineering requirements, whose evaluation is straightforward, a mission's science objectives cannot be quantified by metrics but are defined more broadly. Determining the degree to
which these objectives are accomplished is subjective, in part because the SEI science program combines several disciplines. Moreover, science performed during missions to the Moon and Mars will comprise observational, experimental, and theoretical elements.

The SEI science program and its potential return can be visualized by defining how a given architecture drives a particular parameter affecting science return. This visualization helps planners to see which mission elements most affect the science program. Certain elements affect science return for the overall program and for specific disciplines. During planning, these elements can be configured in the best possible way to ensure a varied and productive mission.

The SEI enables unique scientific investigations on the Moon and Mars. A diverse community is devising sets of questions that scientists must answer to better understand the universe and our place in it, independent of mission architecture. How were the Earth and Moon formed; what was their early history? Did life ever arise on Mars? What is the relationship among the Sun, planetary atmospheres, and climate? Are there worlds around other stars? What is the fate of the universe?

These questions encompass many other science goals, including understanding the origin of the Earth-Moon system, the geological evolution of the Moon and planets, the nature and evolution of stellar bodies, the existence of planets around other stars, the nature of interplanetary particles and fields, and the climate history of Mars. Other issues in applied science, such as materials science and human health and performance in space, will also be advanced by SEI.

The pursuit of high-level science questions is independent of architecture or mission. By contrast, science opportunities involve either the specific experiments made possible by an SEI architecture, or general opportunities that result from the properties of the body being studied. An example of the latter would be using the Moon as an airless, stable, slowly rotating, low-gravity platform for observing the universe.

Science requirements dictate how we
go about answering a question or addressing a problem—what data do we need to take, what observations must we make? The final step is implementation—how we satisfy the requirement using a particular experimental process or instrument.

Scientists are currently defining objectives for astrophysics, geoscience, space physics, biology, and materials science at lunar and planetary bases. Geologists want to explore and sample specific features on and below the lunar surface, from disparate sites including the poles and the far side. Astronomers want to place observatories at latitudes that permit the best view of the entire sky and the least noise interference from Earth. Space physicists want to emplace sensitive detectors that are oriented optimally for measuring particle density and flux.

Because SEI science objectives are defined broadly, and the requirements for “good” science are subjective and difficult to quantify, evaluating architectures for the degree to which they accommodate many disciplines requires a fresh approach. We propose a method for visualizing the science return in terms of parameters that “frame” each discipline. These can be used to describe the amount and quality of science performed for the entire mission program.

Science return can be characterized in terms of three parameters: time, access, and capability. Time includes the days on the surface of the Moon or Mars and the number and duration of extravehicular activities for the mission. It may also include the number of visits or sorties to a designated site of interest. Access is the means for reaching selected sites on a given planet and includes the numbers of sites visited (by human or robots), frequency of visits, vehicles for transporting or delivering crew or hardware, and the mode of travel over a planetary surface.

Capability is more difficult to quantify. It involves the mass and quality of scientific instrumentation delivered to the surface, the number of experiments performed, and the local mobility. Capability is also the number of crew members available for science duties, including their combined skills for conducting experiments and making observations. It also includes the means for sampling the lunar or Martian surface or subsurface by digging, trenching, or coring. Another element is the amount and quality of data and observations that equipment or crew can gather while traveling to or roving between study sites—“traverse science.” Finally, capability involves the amount and sophistication of infrastructure support at an outpost or site; this includes power, data links and storage, lab space and instrumentation, and crew.

If we think of science return in terms of these three parameters—time, access, and capability—we can envision a three-dimensional plot that represents a “mission envelope” for science. This plot defines a space within which a given architecture’s return can be measured. In general, the larger the area of the triangle defined by the three-point plot on the axes, the greater the science return. This envelope or threshold illustrates the science return and allows us to make architectural decisions.

Missions are commonly partitioned into phases, and science is accomplished to different degrees during particular phases. For an architecture that progressively builds up a supporting infrastructure, the collective science return may be quite minimal in early phases, but robust during later phases when the mission can support an aggressive, multi-
disciplinary science program.

Different disciplines may be favored during different phases of a mission. The return for geosciences may be high during an early expedition phase, for example, but much lower once exploration is restricted near the outpost. In the same architecture, astronomy may be neglected during the expedition phase, but could then become quite robust once the outpost can support large observatories, which require great mass delivery and power consumption.

Evaluating "total science return" in terms of access, time, and capability is clumsy, because it lumps all disciplines together. In reality, specific disciplines are leveraged to different degrees by the various framing parameters. It is more useful to consider the disciplines separately, characterizing each one by the factors that most affect the achievement of science objectives. We do this for geosciences, astronomy and astrophysics, and laboratory sciences, plotting each discipline separately on a three-axis graph of access, time, and capability.

Scientific exploration of the Moon and Mars can tell us about planetary processes and reveal subtleties about the formation of terrestrial planets and the solar system. Both the Moon and Mars have complicated histories, and a variety of processes have operated at different rates, in different places, and at various times. Thus we must be able to visit planetary crusts at many sites to comprehend them fully. The factors that most strongly affect return for geoscience are access, time on the surface, and the mobility systems available to deliver a crew to a study site. Return increases greatly with the number of sites visited, because more environments can be characterized, more geological processes and units can be studied, and the potential for unexpected discovery is much greater.

More frequent and longer excursions for studying geologic features allow for real-time assimilation of data and observations, or more simply, for time to think. Longer missions allow for on-site sample analysis. Analyzing rocks in real time allows the crew to rethink subsequent excursions, target new sites, or return to earlier sites. The most important "secondary" parameter of capability in geoscience is mobility, because it enhances access. Mass delivered to the surface is of lesser importance; geologic field tools, because they are carried by the explorer or on a rover, are lightweight and fairly compact.

The Moon is an ideal platform from which to observe the universe. Its high vacuum, cold, dark sky, low gravity, seismic stability, and low noise background at radio wavelengths on the far side make it a unique resource for astrophysical and space physics observations. Astronomical observatories located there would enable high-resolution views into our and other galaxies, a search for planets around other stars, and continuous monitoring of our home planet. Sensors could observe the entire spectrum of wavelengths. Exotic particles and plasmas impinging directly upon the surface, which could be collected for study.

Sites on the lunar equator offer continuous views of the entire sky, but polar sites may be preferable for some observations and viewing techniques. For radio observations, the far side, permanently shielded from Earth's radio din, remains a desirable location.

For astrophysics and space physics, the infrastructure support that enables delivery, assembly, construction, operation, maintenance, and data return from surface observa-
Different "return envelope" for each discipline can be seen on three axis plots. Geoscience is dominated by access and time; capability is largely determined by local mobility. Astronomy and astrophysics are dominated by time and capability; access is of much lesser importance. Lab science is dominated mostly by capability and time. Because it is done at the outpost, it usually has no access requirements, thus producing a two-dimensional surface on this plot.

For lab sciences, the quality of experiments is linked to the amount of space dedicated to experiments and instruments. More space in the lab means that more instrumentation can be accommodated, allowing more complex and varied procedures. Lab experiments might include rock and soil sample examination and analysis, evaluation of planetary materials for resource extraction, biomedical and biological experiments, and agriculture. Secondary factors providing high leverage are trained crewmembers to conduct the experiments and sufficient time for performing them. Lab science would be largely site-independent, making access the least important parameter.

To be evaluated for science efficacy, an architecture must be considered in light of both total science return and specific yield. For example, the scientific return from the Apollo program can be plotted. Then, it can be examined in terms of the Exploration Emphasis architecture, which stresses multiple-site reconnaissance, and the Expanding Human Presence architecture, which features infrastructure build-up at a single site.

The Exploration Emphasis architecture can be pursued at a modest or aggressive level; the choice is likely to be driven by fiscal and operational constraints, not scientific considerations. However, our process permits us to see the relative scientific return, both by discipline and collectively, for different implementations of the same architecture.

Beyond the obvious relation that more capability produces greater scientific return, we see that the Exploration Emphasis architecture yields the greatest leverage for geoscience. Astronomy has a poor return in modest implementations of this architecture, but becomes quite robust at a more aggressive level. Laboratory sciences fare poorly in this architecture, whatever implementation is selected. This is not surprising, because the architectural theme stresses exploration, mobility, and access. The cumulative science return is quite high, whichever implementation is selected.

The Exploration Emphasis architecture is very productive scientifically, particularly in planetary geoscience. Total science return is greatly increased by selecting 45-day surface times over a single lunar-day (14-day)
stay. On the other hand, increasing landed mass does not increase the science return at the same rate. Thus, this architecture, while robust for science in general and geoscience in particular, can be made even more productive with specific choices (for example, stay time), yielding maximum leverage in the science return.

In addition to helping us select options for a given architecture, our evaluation can help to distinguish different architectures in terms of science return and discipline emphasis. The Expanding Human Presence architecture emphasizes the rapid buildup of infrastructure and people at a single site on the Moon. Such a scenario produces a far different return for science than does the Exploration Emphasis approach.

Because the Expanding Human Presence scenario involves high levels of delivered mass, continuous crew time, and large amounts of leveraging infrastructure, both astronomy and lab sciences have a very high return. But access, important for geoscience return, is minimal in this architecture; thus, the return for geoscience is significantly lower than it is in the previous example.

While both architectures produce high scientific return, the Expanding Human Presence scenario offers significant advances to the observational and lab sciences, whereas the Exploration Emphasis scheme makes its major contribution to geoscience. This methodology illuminates differences between architectural themes, in addition to aiding in implementation choices.

Choices of architectural themes and SEI mission goals are policy decisions made at the national level. These thematic decisions set boundaries within which engineers must make implementation decisions. Such architectural details are driven by cost, schedule, and performance constraints. Myriad choices are possible, and many may be more or less equal within the overall constraints imposed by the program’s scale and mission envelope. It is for use at this level that our method is intended.

Science is a vital part of the Space Exploration Initiative. Our goal is to maximize the scientific return of architectures by illuminating and distinguishing choices for various disciplines. Examining the degree to which science objectives are met can help planners design a mission that meets desired goals, while at the same time providing for a rich and previously unimagined harvest of scientific knowledge.

Engineers believe that they can reduce HSCT NOx emissions if they can burn fuel at high enough temperatures.

“Our goal is to produce a component that can survive 1,371-1,650 °C for 18,000 hr,” he says. “That’s longer than existing combustor liners on subsonic transports, which reach their highest temperatures on takeoff and then drop back during cruising. The HSCT will remain hot at supersonic speeds, then drop off during subsonic and landing.”

This poses a very severe requirement. The alternatives to ceramics include less durable combustor liners made of other materials, or air-cooled but less efficient liners that operate at lower temperatures. The key barrier is the environmental resistance of silicon carbide and other promising ceramics at such high temperatures.

Despite all the technological progress, questions about cost and new applications abound. “The major problem with titanium composites is that, without a high-volume commercial application, they remain extremely expensive,” says Reimann. “Even the defense industry needs something to get over the cost barrier.

“With the downturn in defense, I don’t see at this time the defined systems that will require TMC in their engines. We can’t take advantage of titanium composites on a substitutional basis. We need to redesign the entire engine core,” he says. Until engineers define new systems, there will be no new applications to push advanced materials out of the laboratory.

Of course, a show of interest by industry can propel a material into wider use. It could happen with gamma titanium aluminide, where General Motors and Ford Motor have both shown interest in them for valves and other lightweight, high-temperature components. Detroit could use 5 or 6 million lb/yr—more than aerospace manufacturers could absorb in decades, says Reimann—and push prices down to the commodity level.

“Most everyone in the industry understands how lack of commercial use of these technologies has kept costs high to aerospace,” concludes Dimiduk. “We’ll see things change over time as military researchers look for nonmilitary uses to support an infrastructure and keep costs low for military.”

It is a whole different way of thinking. But without it, and without new programs to commercialize new technologies, these almost-ready materials will be all dressed up with nowhere to go.

High-temperature materials
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