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Of red planets and indigo computers: Mars database visualization as an example of platform downsizing

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The last decade has witnessed tremendous advancements in the computer hardware and software used to perform scientific visualization. In this paper, we consider how the visualization of a particular data set, the digital terrain model derived from the Viking orbiter imagery, has been realized in four distinct projects over this period. These examples serve to demonstrate how the vast improvements in computational performance both decrease the cost of such visualization efforts and permit an increasing level of interactivity. We then consider how even today's graphical systems require the visualization designer to make intelligent choices and tradeoffs in database rendering. Finally, we discuss how insights gleaned from an understanding of human visual perception can guide these design decisions, and suggest new options for visualization hardware and software.

Just over 20 years ago, NASA launched the Viking 1 and Viking 2 on their mission to Mars. The primary mission of Viking's robotic landers was to determine whether life had ever existed in any primitive form on the red planet. In support of the missions, the two Viking orbiters collected imagery of the planet surface. The initial objective of this visual imaging work was to characterize potential landing sites in support of site selection. (As it happened, the original landing sites for both Viking landers were deemed unsuitable based on orbiter image data; alternate sites on Chryse Planitia and Utopia Planitia were selected.)

Ultimately, the orbiters were able to map approximately 97% of the Martian surface, returning to Earth over 52,000 separate image samples subtending 1.5° × 1.7°. These images were combined to form a mosaicked digital image model (MDIM); the MDIM compensated for lighting and camera angle effects. Researchers at the USGS working with NASA Jet Propulsion Laboratory then used methods of stereoscopic photogrammetry to create a digital terrain model (DTM) with a resolution of 1 pixel per 1/64° (meaning each pixel subtends just under 1 square kilometer) (Eliason, Batson, & Wu, 1992). The complete DTM database (including its correlated color data) requires approximately 1 GB of storage, a rather daunting size at the time of its generation (the mid-1980s).

In this paper, we will discuss four efforts to visualize this terrain database. These projects illustrate the increasing capabilities and affordability of scientific visualization platforms. In particular, developments in computer graphics hardware over the past decade enable the possibility of truly interactive visualization experiences. However, even with powerful graphics systems, visualization system designers must make intelligent decisions concerning database structure and editing to allow real-time execution. We will discuss how our understanding of human visual perception can contribute to visualization system design, enhancing the apparent performance and making the visualization experience more compelling.

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VISUALIZATION OF SCIENTIFIC DATA

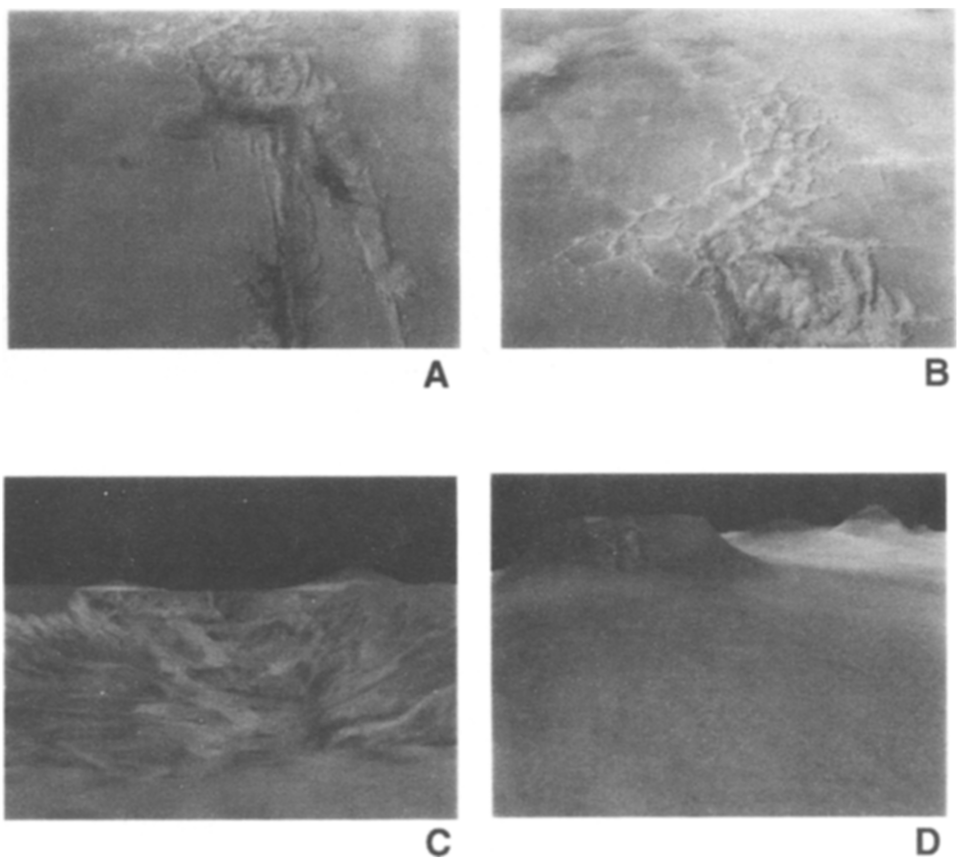
The tremendous advances in computer graphics during the past decade have enabled the development of exciting new data visualization tools. Prior to the development of three-dimensional (3-D) graphics engines, visualization of 3-D data was a painstaking process, involving time-consuming hand drawing and often a fair degree of artistic ability (and occasionally artistic license). Advances in computer technology made visualization methods available to practicing researchers, rather than the privileged domain of a few specialized scientific illustrators.

Wolff and Yaeger (1993) provided a useful taxonomy of the types of scientific data typically visualized. These include numeric data, multivariate functions and systems, image data, surface and terrain data, and volumetric data. Visualization of data in the latter two categories has benefited most greatly from advances in computer graphics technology. Advanced graphics workstations permit researchers to view 3-D databases from any conceivable vantage point and to alter vantage point (either discretely or along an animation trajectory), often in real time.

The Viking DTM database is an exemplar of surface/terrain data. Its vast size and complexity have challenged visualization technologies. But the reward it affords is significant: the opportunity to see another planet. We now consider four projects conducted during the past decade that shared the common goal of providing a compelling visualization of the Martian terrain.

MARS THE MOVIE (1989)

The first major effort to provide a visualization of the 3-D terrain database was performed by scientists at the NASA Jet Propulsion Laboratory (JPL) in the late 1980s. This same team of image-processing scientists had developed the technique of integrating terrain images and digital terrain models, fusing Landsat photos with USGS digital terrain models to produce LA the Movie in 1987 and Earth the Movie in 1988. Working with the DTM and MDIM, the JPL team developed the texture-mapped 3-D terrain model for a sizable patch of the Martian sur-



A B C D

Figure 1. Four sample frames from Mars the Movie: (A) a west-looking view from 125 miles above the surface of the western portion of Valles Marineris; (B) Layrinthus Noctis, an intricate system of interwoven canyons west of Valles Marineris; (C) a view from the edge of Ophir Chasma, the northern part of Valles Marineris (Pavonis Mons and Ascraeus Mons, 1,900 miles away, are visible in the background); and (D) a northern view of Tharsis Montes, a series of giant volcanoes, taken from an elevation of 20 miles above the surface (Arsia Mons is in the foreground, in the center is Paronis Mons, to the right is Ascraeus Mons, and far right is Tharsis Tholus).

face (approximately 60° longitude × 40° latitude). They then designed an eyepoint trajectory for the "virtual journey." The eyepoint varied substantially in altitude (ranging from 2 to 500 miles above the surface), and the orientation of the eyepoint relative to the direction of motion varied from 0° (i.e., gaze angle aligned with direction of motion) to 90° (i.e., a purely lateral motion). Individual image frames were generated on a multiprocessor Cray supercomputer and transferred to high-resolution videotape. The resulting fly-over animation is a bit under 5 min in length, and it highlights some of the more striking features of the Martian surface. Sample frames from the animation are shown in Figure 1. (We are unable to reproduce the color in this and the following figures.)

Mars the Movie (NASA Jet Propulsion Laboratory, 1989) was a stunning achievement at the time of its production, both in terms of demonstrating state-of-the-art computer graphic rendering and in making accessible to a large audience the astounding geology of the Martian planet. Upon viewing the film, the viewer feels that, in some sense, he/she has visited Mars. However, the limitations of the film as a visualization experience are evident. The viewer can traverse only the single trajectory (and its corresponding viewpoints and velocities) chosen by the JPL team. (Some effort was made to provide several views of significant features by integrating loop-backs into the trajectory, but visual exploration is, of course, completely constrained.) In addition to the lack of interactivity, several limitations of the database create annoying artifacts: There is no sky model (the terrain is depicted against a black background), and the edges of the terrain sample are clearly visible, creating unusual (and often angled) "horizons." The simulation is purely visual, although a voice introduction and a music soundtrack (Gustav Holst's "Mars, the Bringer of War") was overdubbed on the videotape. Despite these limitations, Mars the Movie demonstrated effective techniques for visualizing planetary terrain, and it remains a compelling example of the art.

MARS NAVIGATOR (1991)

The Advanced Technology Group at Apple Computer wished to create an exhibit for the Tech Museum of Innovation in San Jose, California, that would showcase the possibilities of multimedia visualization. They collaborated with Volotta Interactive Video, Inc., to create the Mars Navigator (Wolff & Volotta, 1991), an interactive multimedia exhibit that allows the user to fly through the equatorial region of Mars. Like Mars the Movie, the terrain images were precomputed (in this case, on a Silicon Graphics VGX machine requiring about 1 min per frame). However, Mars Navigator achieved a remarkable level of interactivity by allowing users to select their path at var-

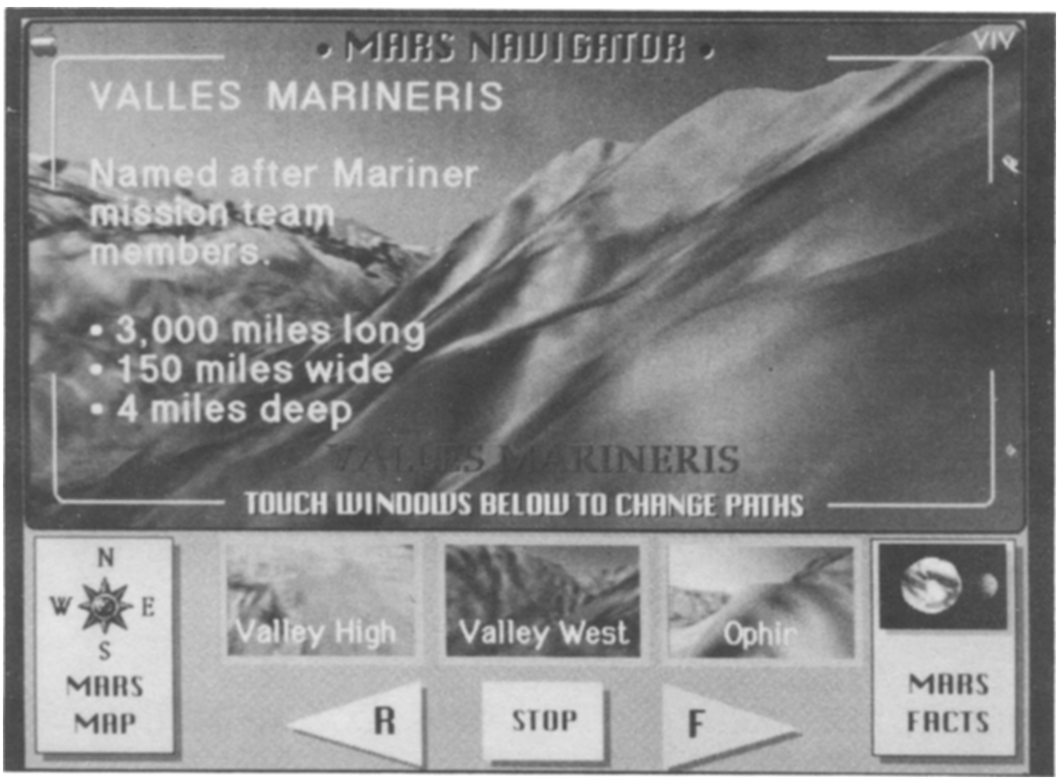


Figure 2. Sample of the Mars Navigator touch-sensitive display screen. The windows at the bottom of the scene show the user's choices for the exhibit at this juncture, providing outer-loop control. Information about the current terrain scene (Valles Marineris) is superimposed via a graphic overlay.

ious choice points, stop at any point along the path, access informational clips, and view other flight path options. This was done by mastering animation sequences onto a laser disk; an Apple Macintosh IIfx computer could access either of two laser disk players (the dual system allows seamless switching). The Mac also hosted sound files and graphic overlays and processed control inputs from the touch-screen display. The exhibit thus gives the users a sense that they control the course of events in the exploration. A sample display screen is shown in Figure 2.

Mars Navigator also made several improvements to the quality of the visualization—most notably, the addition of a Martian atmosphere. There was also the addition of ambient sounds (e.g., engine noise), which enhances the user's experience of immersion.

In fact, Mars Navigator is such a compelling visualization experience that the user becomes fairly unaware of the constraints the system imposes. By providing the user a good deal of "outer-loop" control options (e.g., which path to take, when to access additional data sources), the designers disguise the lack of true "inner-loop" control (i.e., the fact that the user is still unable to define the eyepoint, gaze angle, and trajectory). Mars Navigator is a masterful example of doing a lot with a little (the host computer possessed a single 68030 CPU, a mere 8 MB of RAM, and an 80-MB internal hard drive) by leveraging the capabilities of precomputed imagery and multimedia integration.

VIRTUAL PLANETARY EXPLORATION TESTBED (1991–1995)

The Virtual Planetary Exploration Testbed (VPET) was developed by Michael McGreevy and his colleagues at the NASA Ames Research Center to provide a truly interactive visualization tool for planetary scientists to explore terrain databases (McGreevy, 1991, 1992; Hitchner & McGreevy, 1993). The testbed sought to ultimately provide users with a fully immersive, virtual environment (VE) interface, using head-tracked head-mounted displays, gesture trackers, haptic displays, and 3-D sound to create an artificial world of visual, proprioceptive, and auditory experience. The goal was to provide planetary geologists with a testbed that would support the same exploratory activities they would perform at an actual geological site.

Due to limitations in VE hardware at the time, this goal was not fully realized. Nonetheless, the VPET project achieved the first truly interactive Mars terrain visualization tool. The visual display was a head-mounted color LCD display (the Virtual Research Flight Helmet) with a wide field of view (i.e., > 60 ° per eye); the graphics were driven by a Silicon Graphics 4D/440 dual-channel SkyWriter. Despite its state-of-the-art hardware (for its time), the display had limited spatial resolution, and marginally acceptable update rates (> 5 Hz) could be achieved only by using a sophisticated level-of-detail manager (Hitchner & McGreevy, 1993). The VPET produced an interactive terrain visualization tool, but the hardware platform was expensive, and extensive software engineering (much of it machine specific) was required to achieve marginally acceptable system performance. Nonetheless, the project demonstrated a design path that future systems could successfully follow.

MARS VIRTUAL EXPLORATION CONTROL CENTER (1996)

July 20, 1996, marked the 20th anniversary of the landing of Viking 1 on the Martian surface. Numerous celebrations were held throughout the country, with exhibits contributed by several NASA centers and industry partners who had worked on the Viking missions. One of the exhibits developed at Ames was the Mars Virtual Exploration Control Center (MVECC). The goal of this exhibit was to provide to the viewer the experience of an interactive recreation of the Viking spacecraft's journey, including the planetary approach, terrain flyover of Valles Marineris, and panoramic view captured by the Viking 1 lander at Chryse Planitia. These three segments of the exhibits used different world databases and offered the user differing degrees of interactive control. We will focus our discussion on the flyover segment, since it is most germane for comparison with the other visualization efforts.

The terrain patch available for interactive flight on the MVECC was substantially smaller than that used in Mars the Movie; it subtended approximately 20° longitudinally and 15° in latitude. This was necessary to ensure that the entire terrain and sky model could be loaded into the RAM during the simulation. (This is a limitation that we plan to overcome in a future refinement by adding a terrain swapping capability; database and simulation development for the exhibit was extremely time constrained.) However, this constraint in exploration space was fairly transparent to the users, since the time they were allowed in the flyover segment was limited, and they were given a specific search task that kept them well within the confined region. In principle, the system could provide users with full 6 *df* control. In practice, we found it most useful to constrain eyepoint orientation and velocity, and allow the users to control directional heading. Soft boundary constraints were imposed so that the users could not exceed upper and lower altitude bounds, nor could they journey so close to the edge of the terrain model that horizon artifacts would occur.

We strived to make the exhibit a fairly immersive, multimodal experience. In addition to narration and background music, ambient sound effects were integrated. The terrain and planetary models were rendered in stereo (using LCD shutter glasses), which supported a sense of viewing the scene through a window aperture. (This percept was further enhanced by the addition of superimposed symbology at the depth plane of the monitor.)

In all, the exhibit provides a compelling visualization experience that conveys much of the splendor and wonder of the Viking mission findings. Admittedly, however, we exploited a number of "Hollywood" tricks to mask the limitations of the visual simulation, such as constraining eyepoint trajectories to areas where database limitations were not evident.

What is most striking about this project is the extent to which it was able to create a visualization system with capabilities equal to or better than its predecessors in a much shorter development period and at a strikingly lower cost hardware platform. The final version of the exhibit can be run on a two-CPU Silicon Graphics Onyx Reality Engine with 128 MB of RAM. Although this is by no means a "desktop system," it is a substantial reduction from the cost of a two-channel SkyWriter (which provided no auditory display), which hosted the only previous system with true interactivity (the VPET). We are hopeful that a minimal version of the simulation can be hosted on a desktop SGI system, such as an Indigo High Impact.

Perhaps more noteworthy is the reduction in development effort for this visualization effort compared with earlier efforts. Our system was exhibited about 8 months after serious effort was initiated. (Even then, the development team consisted of only two software engineers, neither of whom could devote their full-time effort to the project.) Much of the time savings was realized by the improved availability (and portability) of the terrain data sets. Our project spent approximately 3 months acquiring and formatting the necessary databases; the team for Mars Navigator spent over 2 years (Wolff & Yaeger, 1993). Furthermore, our efforts were greatly aided by modeling and simulation tools and programming libraries (notably, World Tool Kit, produced by Sense8 Corporation) available on today's graphic workstations.

THE ROLE OF PERCEPTUAL TUNING

The review of these projects attests to the impressive development in visualization tools over the past decade. Hardware platforms have gotten cheaper and faster, and software tools are strikingly better (reducing application development time and cross-platform porting difficulties). In fact, given the improvements in visualization capabilities (and the concurrent reduction in system costs), one might suppose that the problem of developing effective scientific visualization systems will be fully solved by advances in the computing industry. Of course, this overlooks the vital role of content providers (i.e., those collecting and selecting the data to be visualized) and the critical contribution of human–computer interaction researchers in developing effective interfaces.

Even with increased graphics and computing capabilities, it is not possible for even the most sophisticated VE systems to fully recreate the perceptual complexity of a natural environment. Thus, designers must make intelligent decisions concerning how to reduce displayed complexity without overly impacting the conveyance of information critical to the visualization experience. These choices can be driven by aesthetics and engineering as well as psychology, but there are important insights that the perceptual psychologist brings to bear on the decision process (Kaiser, 1996).

One example of these design decisions germane to terrain data visualization concerns the degree of vertical exaggeration that should be applied to the database. Generally, it is known that the vertical extent of objects become apparently compressed when viewed from a high or overhead vantage point (Wolff & Yaeger, 1993). Thus, it is common (even with physical relief maps) to introduce an exaggeration of height. For example, a 4× vertical exaggeration results in a mountain that is 5,000 ft in height being depicted as 20,000 ft in height. Most visualizations of the Mars DTM employ vertical exaggeration: Mars the Movie used a factor of 5; Mars Navigator used a factor of 6. However, although this exaggeration is useful for depicting vertical extend from high eyepoints, it can create distortions in the depicted topology when viewed from a lower eyepoint. Consider the example shown in Figure 3.

When viewed from a relatively low altitude of 5 km, a nominal vertical extent (Figure 3B) provides a veridical depiction of the Valles Marineris canyon structure—especially the vast distance between canyon walls. However, the lack of database detail is somewhat bothersome to the viewer at this eyepoint, so it is natural for the viewer to elevate the eyepoint (say to 30 km) to achieve higher apparent detail (Figure 3A). However, at this altitude, the vertical extent of geological features is difficult to discern, such that a vertical exaggeration seems desirable (Figure 3C). But that vertically exaggerated database presents a distorted view of the topology when the eyepoint is lowered (Figure 3D): The angle of the canyon wall suggests a narrower width structure and implicates (to the geologically trained eye) a formation process dominated by water cutting. In fact, seismic activity and wind-based erosion is thought to have played a larger role in the formation of these Martian structures.

How, then, should the designer deal with this problem in a visualization system that allows the user to vary eyeheight? Perhaps the ideal solution would be to have the vertical exaggeration vary dynamically as a function of eyeheight. But this solution is technically difficult, since the database model is typically precomputed (and real-time restructuring would be computationally untenable). Another solution would be to precompute several versions of the database with varying degrees of exaggeration. The users could then employ the database most appropriate for their current visualization activity. The viewing altitudes could be bounded for each database and/or the system could page in the appropriate database as altitude regions are traversed.

The less desirable solution—but one that is usually chosen due to constraints in hardware capability or development efforts (or both)—is to select an exaggeration factor that is the optimal compromise for the likely eyeheights in the current application. For the MVECC, we chose a factor of 2; the choice of a single value was aided by the fact that we placed boundaries on eyepoint altitude. Our consulting planetary expert was relatively satisfied with the choice (more so than with earlier selections).

We have described elsewhere (Kaiser, 1996; Kaiser, Montegut, & Proffitt, 1995; Kaiser & Proffitt, 1992) how knowledge of visual perception and psychophysical methodologies can be used to develop and evaluate rendering techniques that result in significant computational sav-

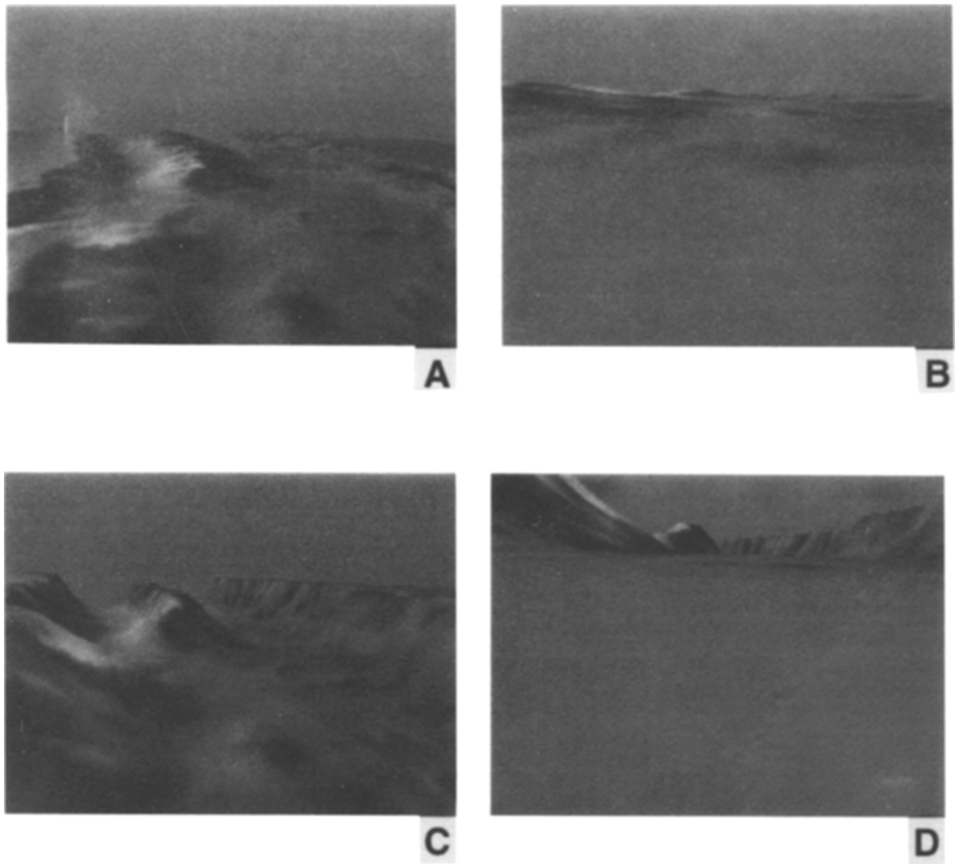


Figure 3. Three views of the eastern end of Valles Marineris demonstrating the effect of eyeheight and vertical exaggeration: (A) 30 km eyeheight and no vertical exaggeration (1×); (B) 5 km eyeheight and 1× exaggeration; (C) 30 km eyeheight and five times (5×) vertical exaggeration; and (D) 5 km eyeheight and 5× exaggeration.

ings for the graphics systems without overly compromising display quality. These techniques exploit the fact that the visual system neither uses nor requires all of the optical information available in a scene when forming spatial perceptions. The perceptual psychologist can and should aid in the development of visualization systems so that efficiency gains can be realized by designing systems that render only information that is of perceptual utility. In that way, visualization tools can become most effective and available to scientists as they seek to understand the mysterious phenomena of our world (and other worlds).

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