Texture Shading: A New Technique for Depicting Terrain Relief

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The Story

- My interest in cartography is from my other hobby – hiking
- Existing maps of my local mountains were unsatisfying
- I was not developing a "mental map," as I had in the city
- What was missing?
- Once I found the answer, I set out to make a different kind of terrain map

My education is in mathematics, and my career is software engineering, but what led me to cartography was my experience hiking in the San Gabriel Mountains near Los Angeles, where I live.

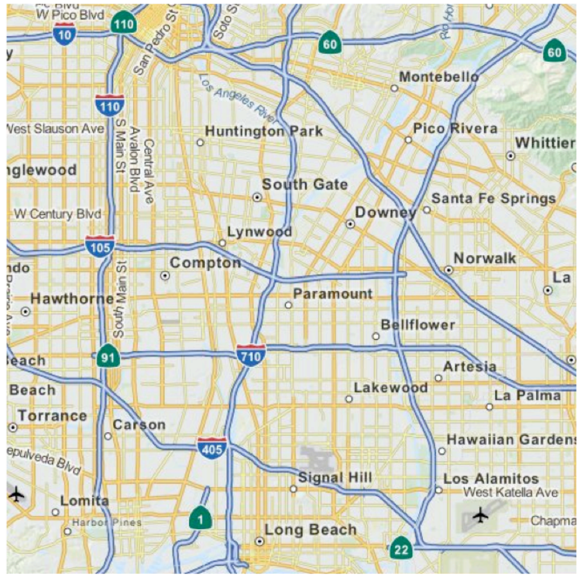
After a lot of time hiking, I found I still didn't have an understanding of the layout of the landscape, as I wanted. I would come to a high point on the trail and look out around me, but I had no idea where I was or what I was looking at. Following a trail guide was like following turn-by-turn GPS directions, with no real awareness of the broader context. I wasn't developing a mental map of the mountains as I had for the city. Existing terrain maps didn't seem to be providing what I needed (with my apologies to the cartographers who made them!).

Some Useful Features of Street Maps

- Network structure
  - Provides “skeleton” for map content
  - Shows relationships between places
- Visual hierarchy
  - Major components stand out
  - Smaller details have *less contrast*

Goal:

Make terrain maps with these characteristics



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Tiles courtesy of MapQuest, http://www.mapquest.com/

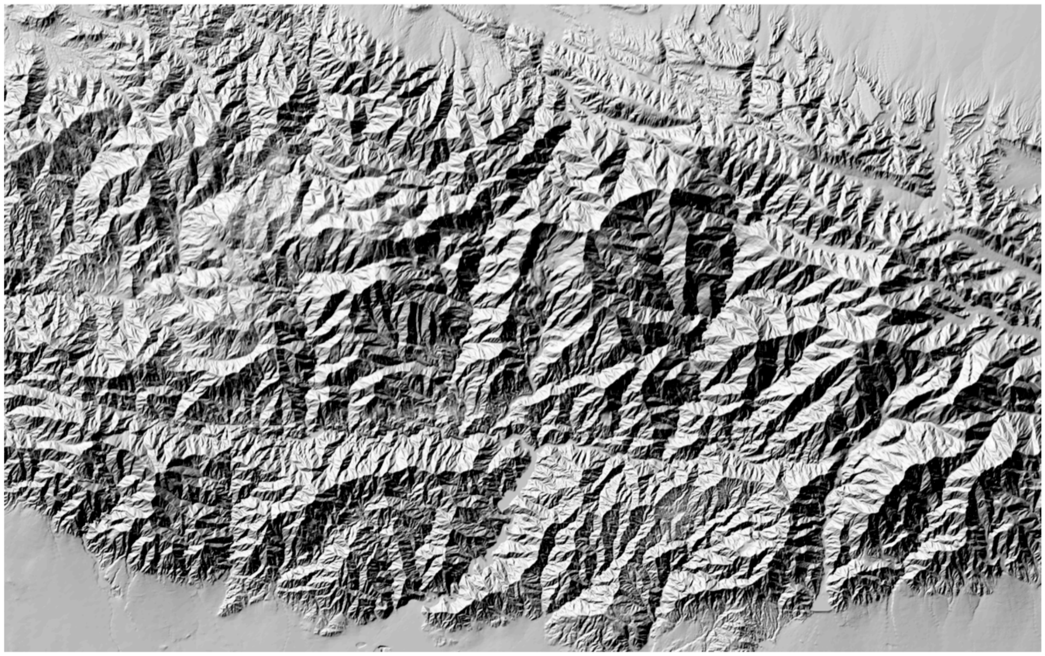
One thing I find helpful about street maps is that they’re built around a network structure. For instance, in L.A. I’ve memorized the freeway system, and that provides a reference for me to locate places. Mentally I know where things are, based on where they are in relation to the freeways.

A network of linear features also provides connections among point features. So on a road map, cities are not just isolated, scattered points on a map, but they’re connected by highways. Likewise in the mountains, point features like peaks are not unrelated, but are often connected by ridges.

Another helpful characteristic of street maps is visual hierarchy. This map has a clear hierarchy that draws your attention first to the freeways in bright blue, and then secondary roads in lighter and lighter colors – and if we were to zoom in, we’d see the individual residential streets in an even more subdued color.

A key insight here that we’ll use later for terrain maps is that lesser features are shown with less contrast.

But Hillshading May Look Like This …



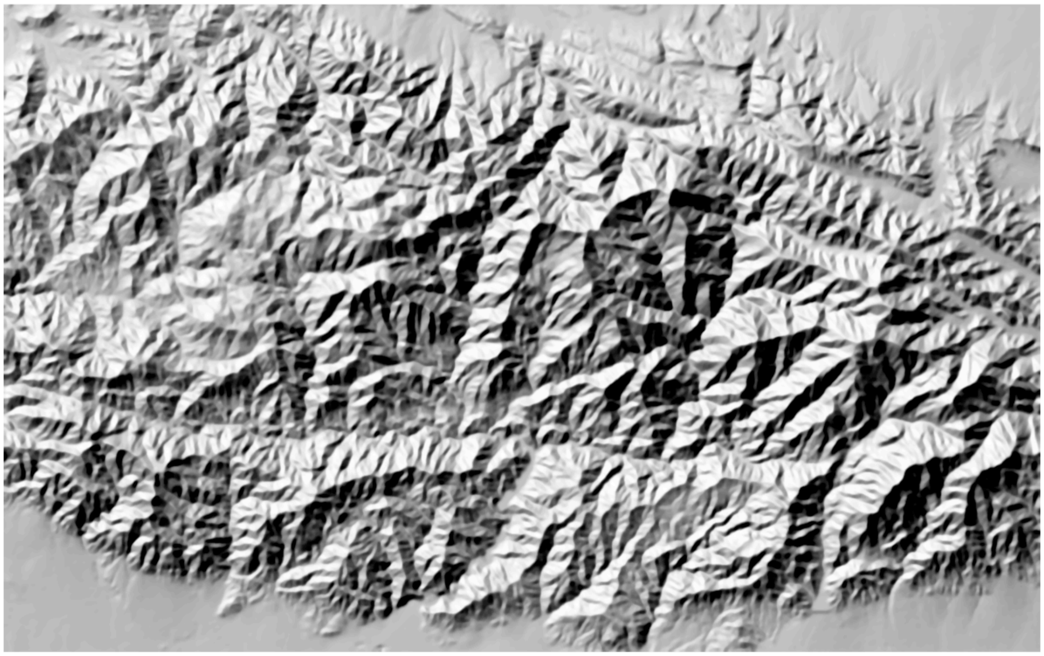
San Gabriel Mountains, CA, USA   Scale: 55 km x 35 km   Data Credit: U.S. National Elevation Dataset (NED)

Here's an example of hillshading, using basic default settings. It has a couple of problems as I see it. The first is that it has no clear network structure. Some of the information may be there if you look hard enough, but it certainly doesn't jump out at the viewer like the freeway system does on the previous map.

Secondly, there's a complete lack of visual hierarchy. The image is cluttered with details, since the shading shows all the slope variations at even the smallest of scales.

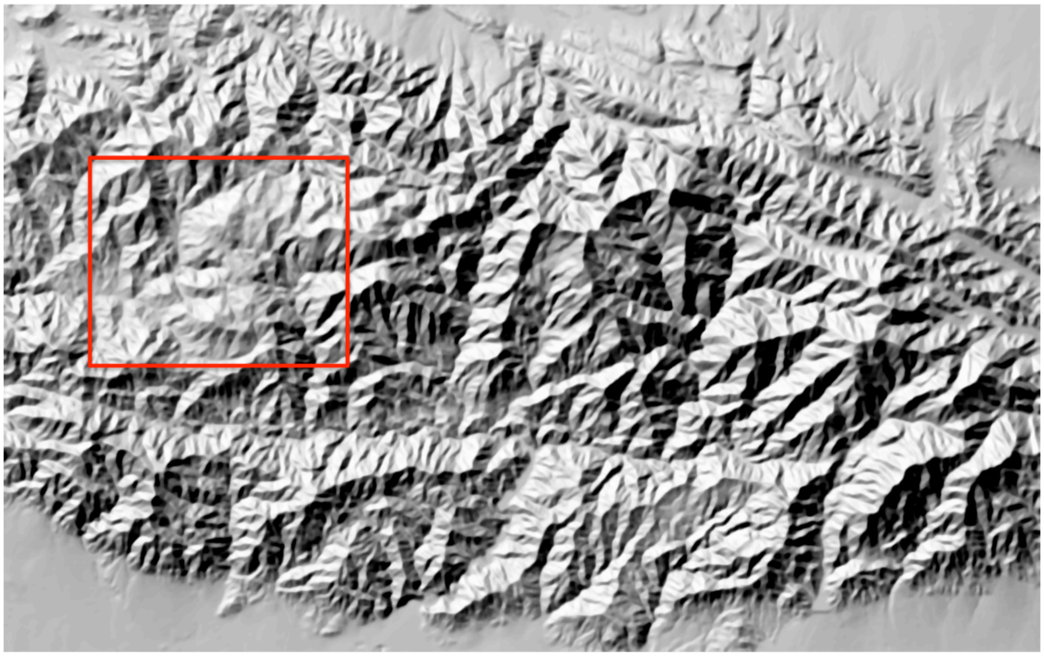
Of course, we can improve on the second problem by generalizing the terrain…

Hillshading (generalized)



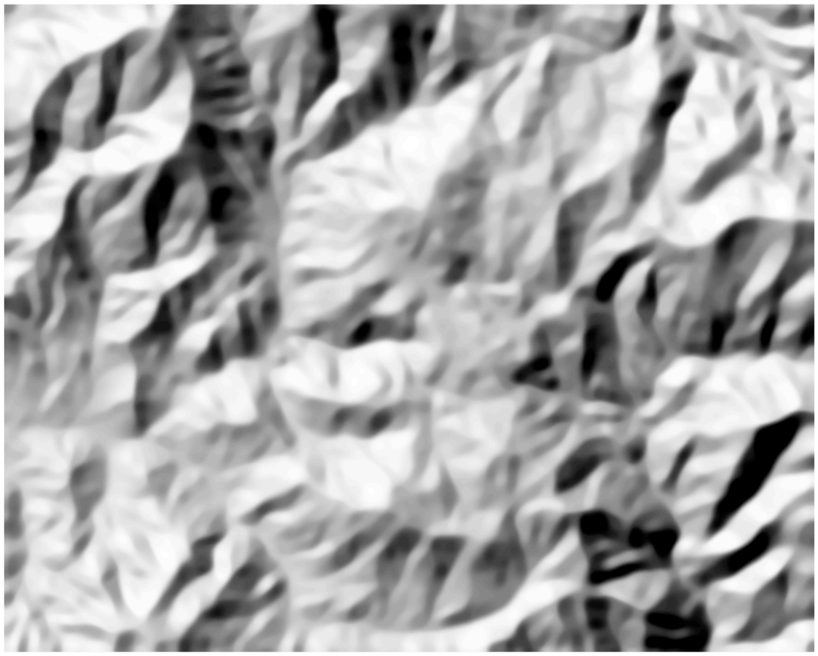
This generalized hillshading eliminates all the details below a certain size, which reduces the clutter and makes it easier to see the major landforms. There's still no hierarchy among the remaining features, however.

Hillshading (generalized)



Now suppose we zoom in on the boxed area on the left, by simply enlarging that portion of the image …

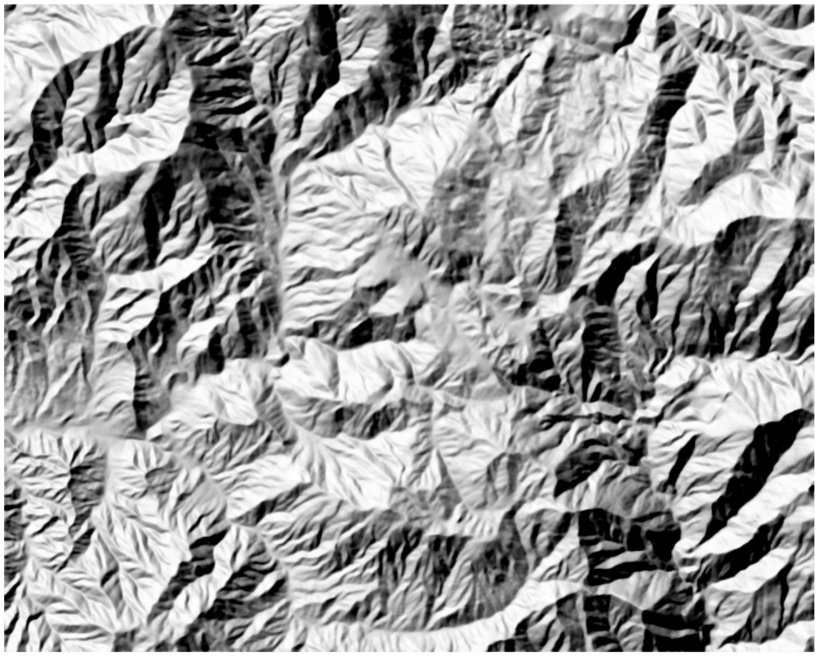
Hillshading (image enlarged)



Scale: 14 km x 11 km

At this scale now there are not enough details. And so we would have to redraw the map for this scale and change the generalization, adding some of the missing details back in …

Hillshading (detail restored)

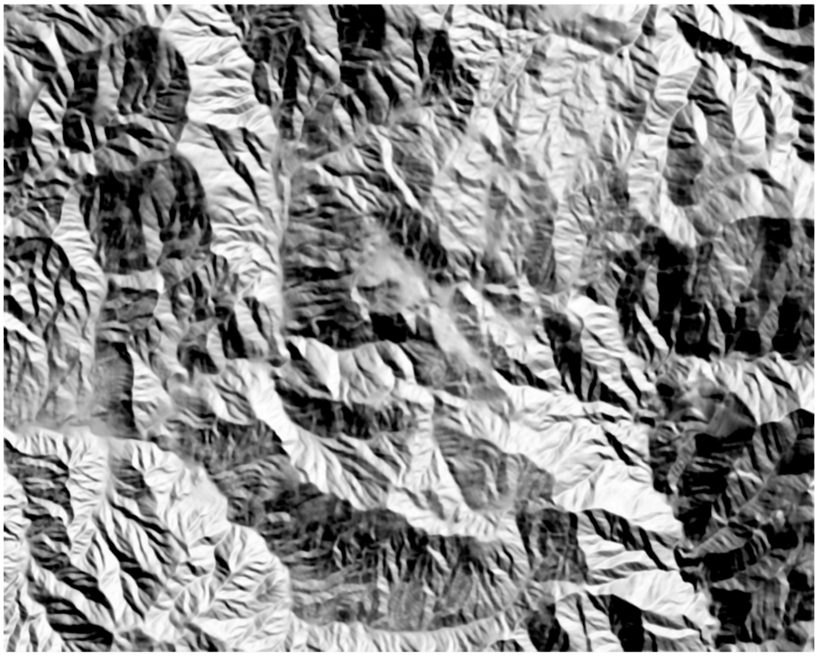


This need to redraw the relief shading for each scale may not seem like a problem – especially when we're used to digital pan-and-zoom maps that use pre-rendered tiles and load new ones whenever the zoom level is changed.

But consider a wall map that will be viewed from different distances. I'd like to be able to produce a wall map where you could walk up and put your nose in the map, and see all the fine details up close; but as you'd step back and view it from across the room, the details would vanish and the only the larger features would be seen. I believe this is something we can actually accomplish.

Likewise even with a digital image such as the one above, the appropriate level of detail depends on the image size and viewing conditions. If viewed on a large screen from a close distance, even more detail may be needed; whereas if it's viewed on a small smartphone screen, this may still be too cluttered.

Hillshading (change of lighting direction)



Another familiar issue that arises with traditional hillshading is that a change of illumination direction makes a completely different map. Features become visible that were unclear before, and features that were clear become difficult to see. And with a single illumination direction, the appearance of features like canyons and ridges depends greatly on their orientation relative to the light source.

The new method solves this problem in part by eliminating the concept of a lighting direction altogether, so that the shading is not based on an illumination model at all.

Common Drawbacks of Hillshading

1. No obvious network structure
2. No clear visual hierarchy
   - Too cluttered with details, or else details absent
   - Single level of detail
     - Appropriate for only a single zoom level or viewing distance
3. Orientation dependence
   - Appearance depends on orientation of terrain features and direction of illumination

This list summarizes the issues with hillshading mentioned in the last few slides.

These three problems then correspond directly to the three goals for the new shading method, which I've called "texture shading" …

Design Goals for "Texture Shading"

1. Emphasize network structure
   – *Canyons and ridges* form the terrain network
2. Scale invariance
   – Visual hierarchy consistent across zoom levels (or viewing distances)
3. Orientation invariance
   – A.k.a. "isotropy"

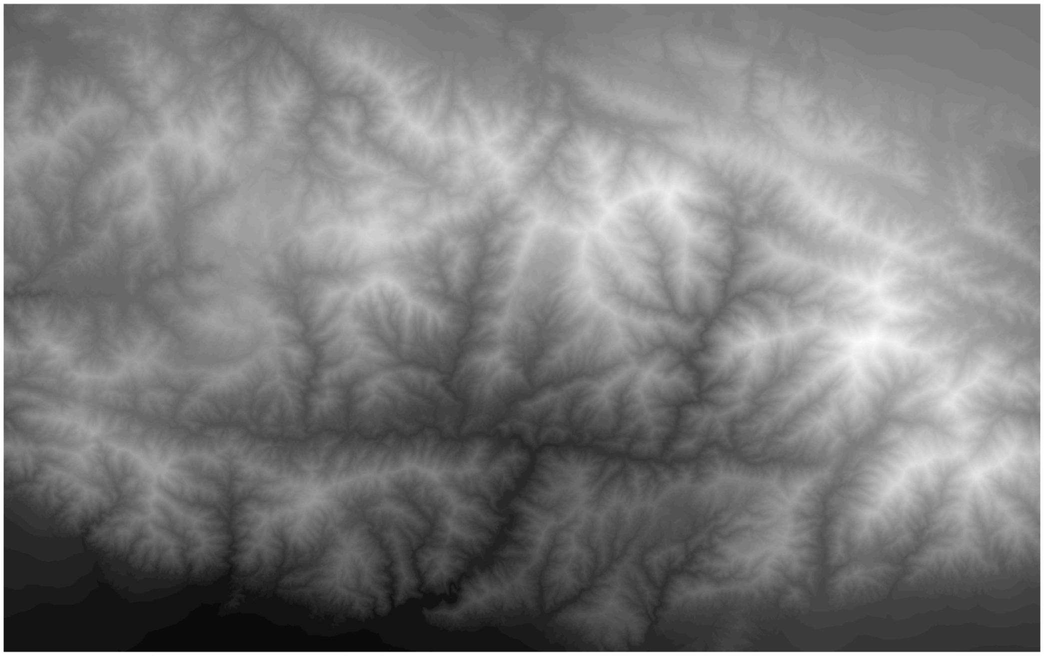
The first goal for texture shading is to show the network structure of the terrain. It occurred to me one day that, at least for muntains like the San Gabriels, it's the ridges and canyons that form the relevant network structure I wanted to see in a map. The day I realized that was the day I really got started on this project.

The second goal, scale invariance, is a specific kind of visual hierarchy. It's a stronger constraint that requires the image to maintain similar characteristics across multiple scales or zoom levels. (In particular, smaller and smaller details will have lower and lower contrast, where the ratio of contrast reduction remains constant at every zoom level. This is akin to the self-similarity of fractals at different scales, and fits well with the fractal-like qualities of actual terrains.)

The third goal is for the shading effect to be independent of the orientation of terrain features. "Isotropy" is the technical term for this property.

Together, these three form a very strong set of constraints, which are almost sufficient to uniquely determine the solution.

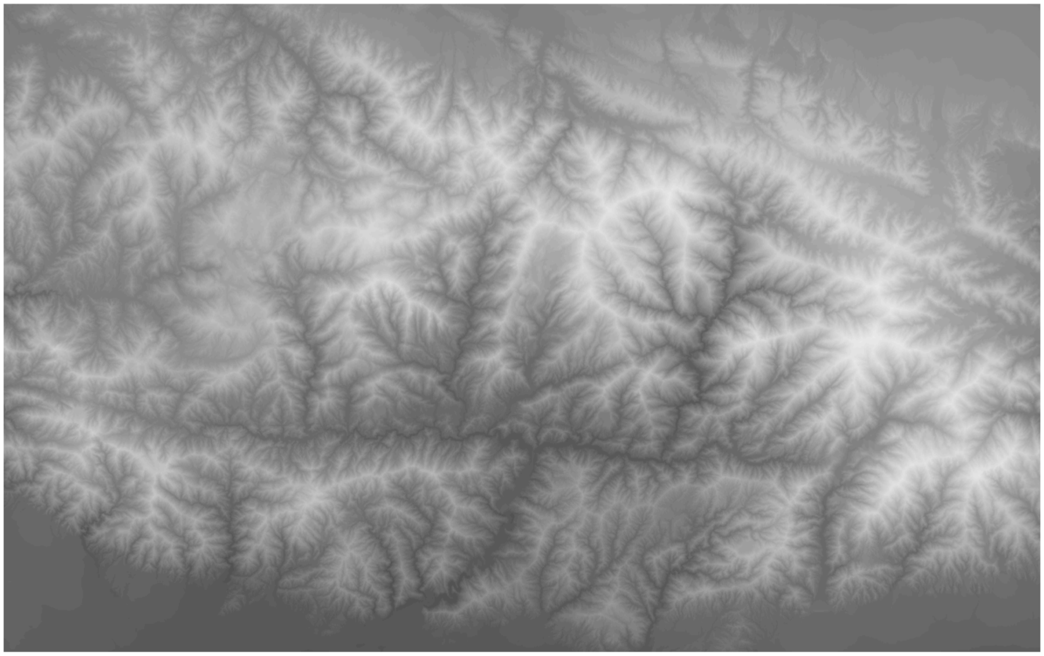
Texture Shading: Detail = 0% (raw DEM)



Now we'll look at texture shading in action. The starting point is a raw digital elevation model (DEM). This image shows the DEM data plotted as a grayscale, where white is high elevation and black is low.

This has the beginnings of the network structure we're looking for. But the smaller details are completely lacking, and the image has a very fuzzy appearance.

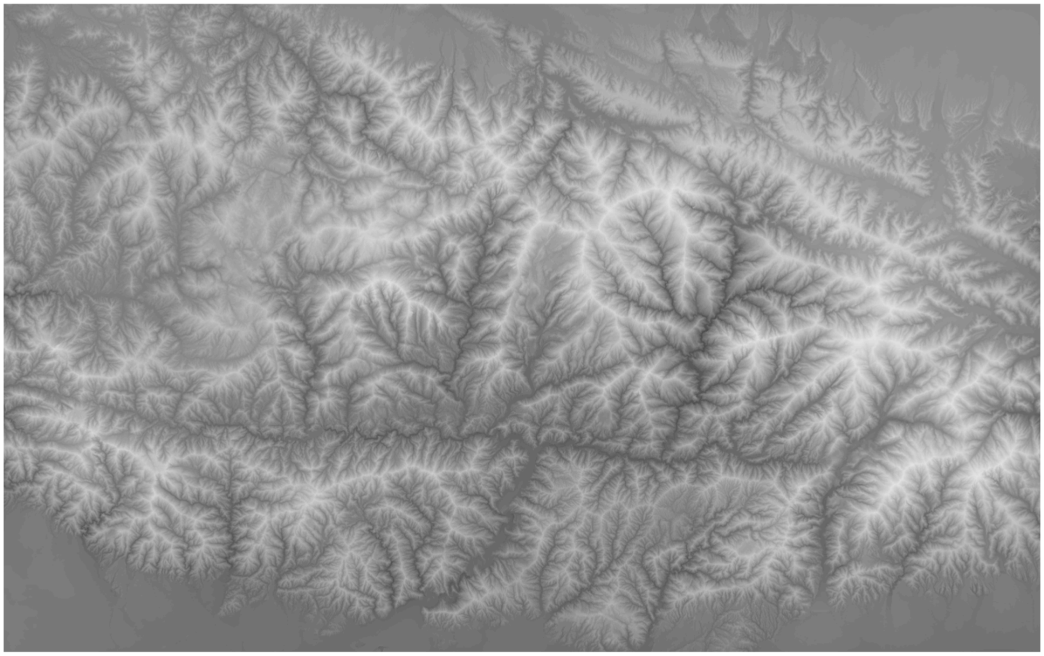
Texture Shading: Detail = 25%



Texture shading has a kind of sharpening effect on the DEM image. Here you can see some of the details becoming visible, and a visual hierarchy developing.

Texture shading has a parameter we can tune, expressed here as a percentage, which controls how much the details are enhanced in relation to larger features. (More specifically, this determines the scale-invariant contrast ratio that was mentioned earlier.) This image uses a detail parameter of 25%.

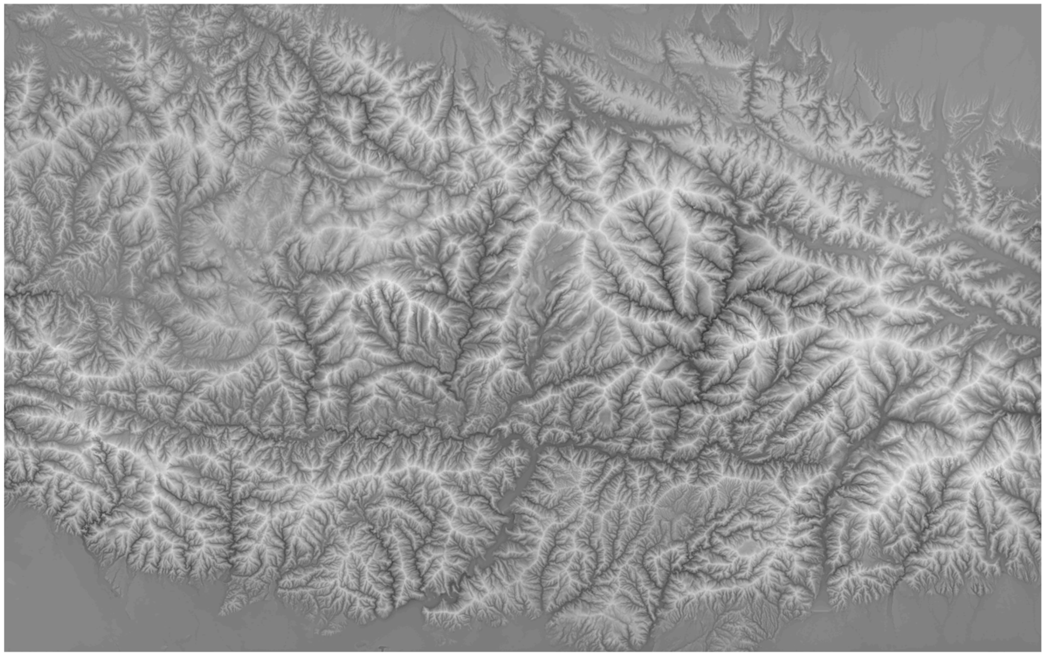
Texture Shading: Detail = 50%



As we turn up the detail value to 50%, more details come into view and the image becomes sharper.

The grayscale values no longer represent absolute elevation, referenced to sea level; that meaning is gradually being replaced with *relative* elevation, relative to the nearby terrain. So light shades represent points which are high relative to the terrain nearby – i.e., ridges and peaks – and dark shades represent points which are low relative to the terrain nearby – i.e., canyons and valleys. (“Nearby” is defined here in a fuzzy way designed to produce the scale invariance property, with more and more emphasis on the closer terrain as the detail percentage is increased.)

Texture Shading: Detail = 75%



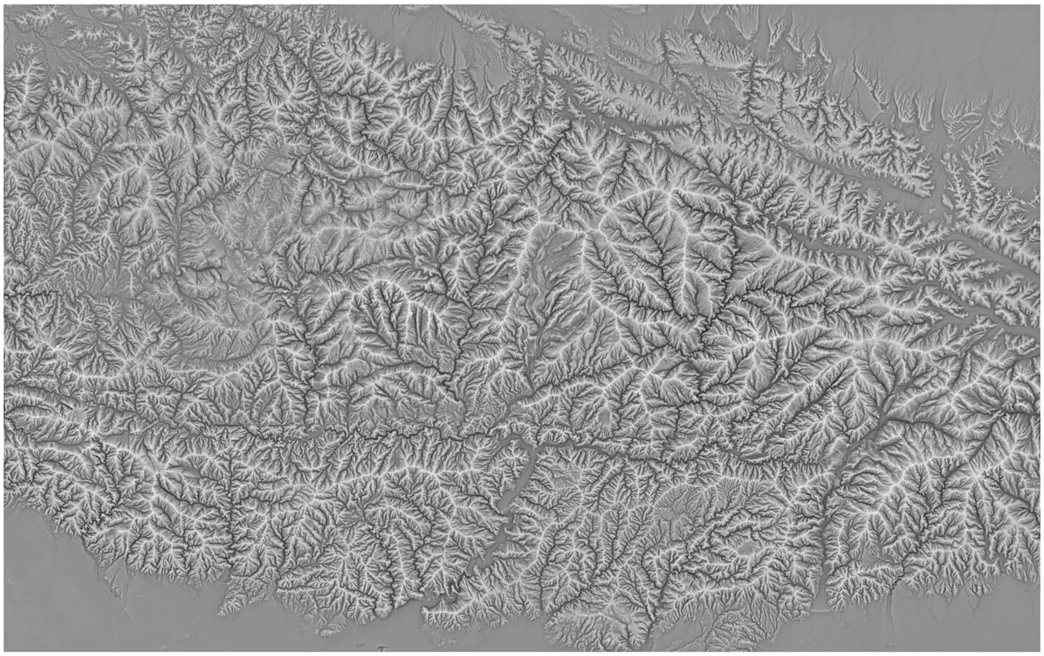
As we increase the value to 75% we see even more detail, and the absolute elevation information is nearly gone.

I typically like to use a value between 50% and 75% for most terrain regions.

Texture Shading: Detail = 100%

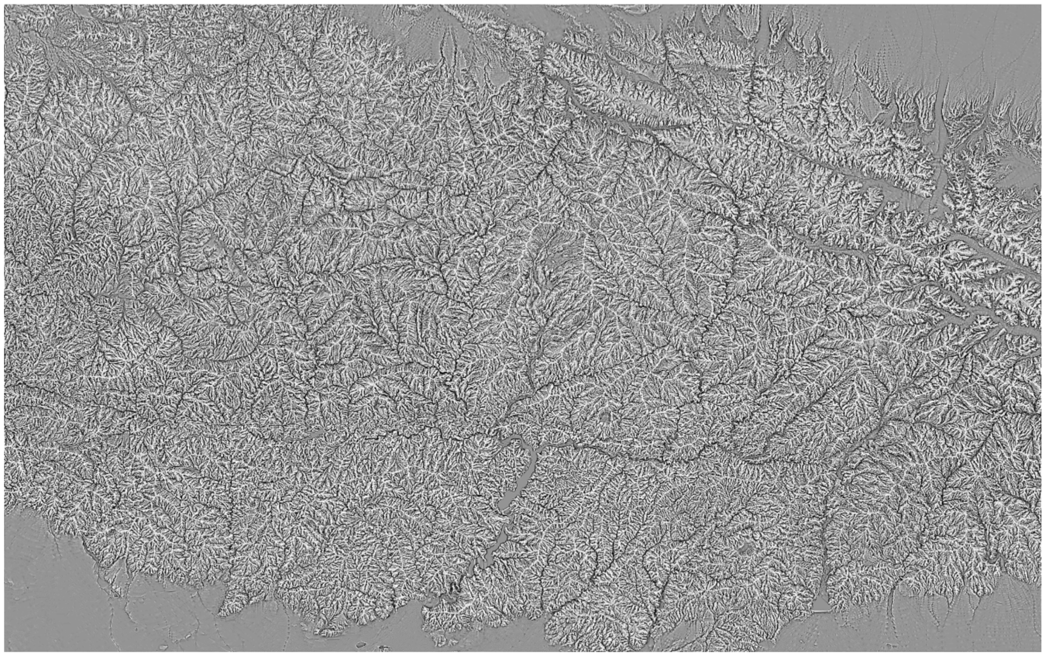
At 100% the details are enhanced so much that we may start to lose the visual hierarchy again.

Texture Shading: Detail = 125%



We can go beyond 100%, which may be useful for certain types of terrain.

Texture Shading: Detail = 200% (Laplacian)



In fact we can go all the way up to the limit of 200%, which produces an image like this one. This may seem ugly, but Tom Patterson has found a way to make use of this output in some cases to simulate rock textures for mountainous terrain. (For more information, see his article at http://www.shadedrelief.com/texture_shading/.)

At 200%, the mathematical operation being performed has a name – it's called a Laplacian operator (after the French mathematician Pierre-Simon Laplace). It's more familiar in the field of image processing, where it produces more useful results and is sometimes used as an edge detection technique.

For values less than 200%, the operator is called a *fractional* Laplacian, which is a lesser-known and more complex function.

What Texture Shading Does

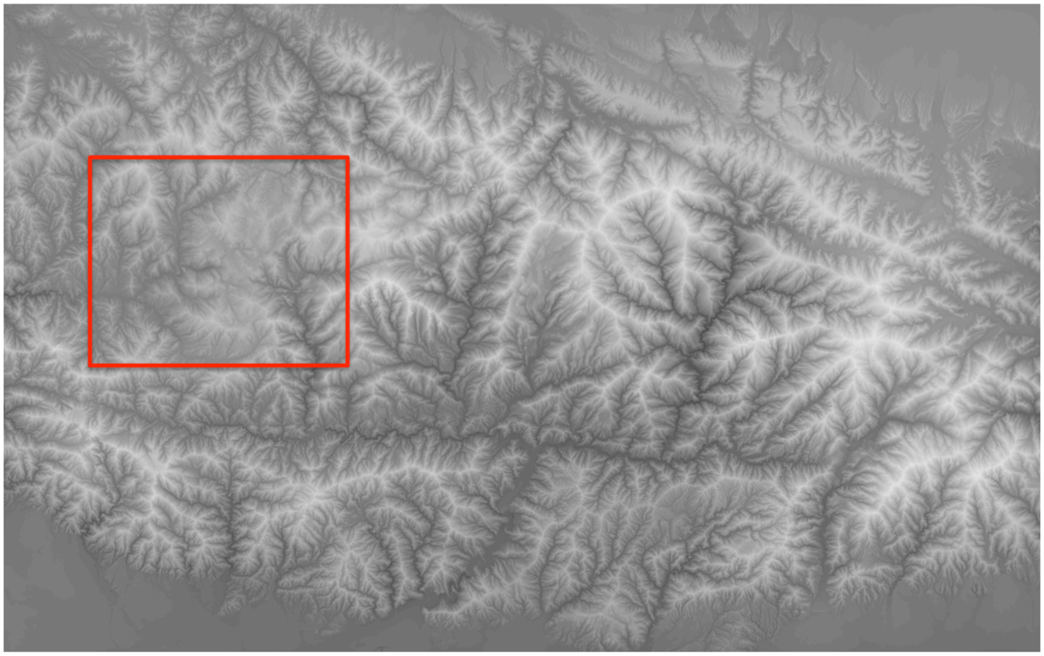
- Two intuitive descriptions:
  - A type of high-pass filter, or sharpening filter, on the DEM
    - Enhances narrow terrain features (details)
    - Attenuates wide features (major landforms)
  - A measure of *relative* height compared to nearby terrain
    - Light areas are higher than nearby terrain (ridges, peaks)
    - Dark areas are lower than nearby terrain (canyons, valleys)
- Mathematical description:
  - "Fractional Laplacian" operator
    - Related to fractals, which accounts for the multi-scale properties
    - At 200%, becomes an ordinary Laplacian (used in image processing)

This slide summarizes the effects of texture shading just discussed.

It's no coincidence that the word "fractional" (in "fractional Laplacian") sounds a lot like "fractal." The two are closely related, and it's this aspect that creates the multi-scale properties of texture shading.

Let's take a look at what we mean by "multi-scale" and "scale invariance" …

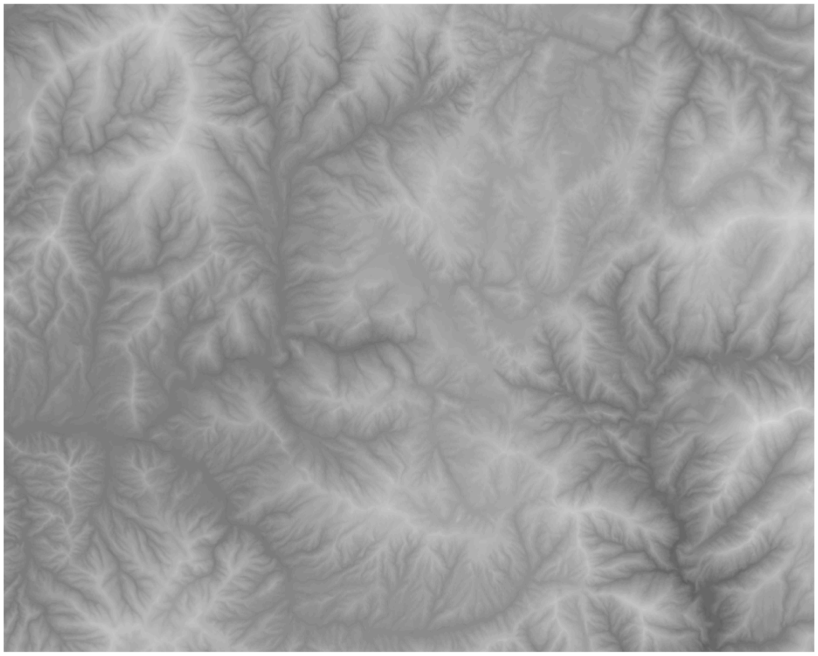
Texture Shading: Detail = 50%



Here again is a texture shaded terrain with a detail setting of 50%.

Let's enlarge the area of the image in the red box that has somewhat lower relief …

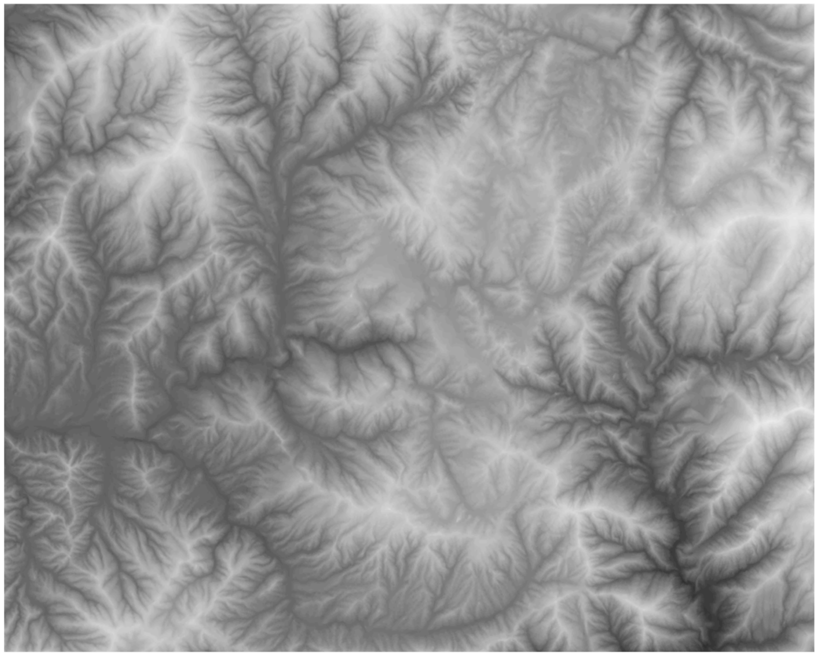
Enlarged Image Retains Detail



Unlike with hillshading, this time the smaller details are present in the enlargement – though with reduced contrast. Because of the reduced contrast, these details don't clutter the larger image or interfere with the visual hierarchy. But they become visible when we zoom in close enough.

Since this smaller region has less overall relief than the original image, the one adjustment we may want is to enhance the contrast at this zoom level …

Adjusting Image Contrast Only

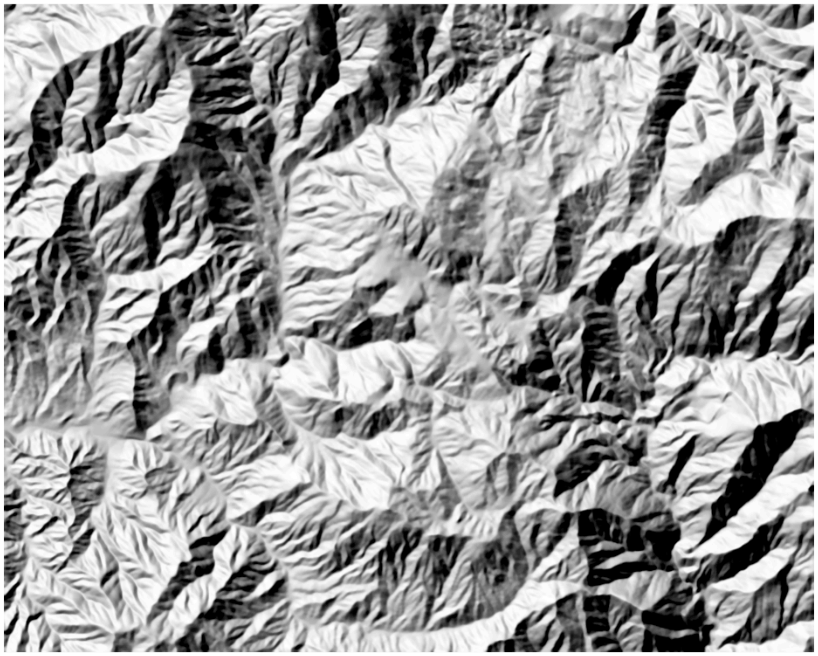


Here we've made no changes other than to adjust the contrast curve from the enlarged image in the previous slide. Thus, a single high-resolution image could be used for all zoom levels, with at most a contrast adjustment peformed, if desired. The contrast can be corrected after the fact, without needing to regenerate the relief for each zoom level. Likewise, a single image should be appropriate for viewing at varying distances; the smallest details will have very low contrast and thus only visible from up close.

Thanks to the scale invariance, this process of enlarging and optional contrast enhancement can be repeated through multiple zoom levels, down to the finest detail that the underlying data can support.

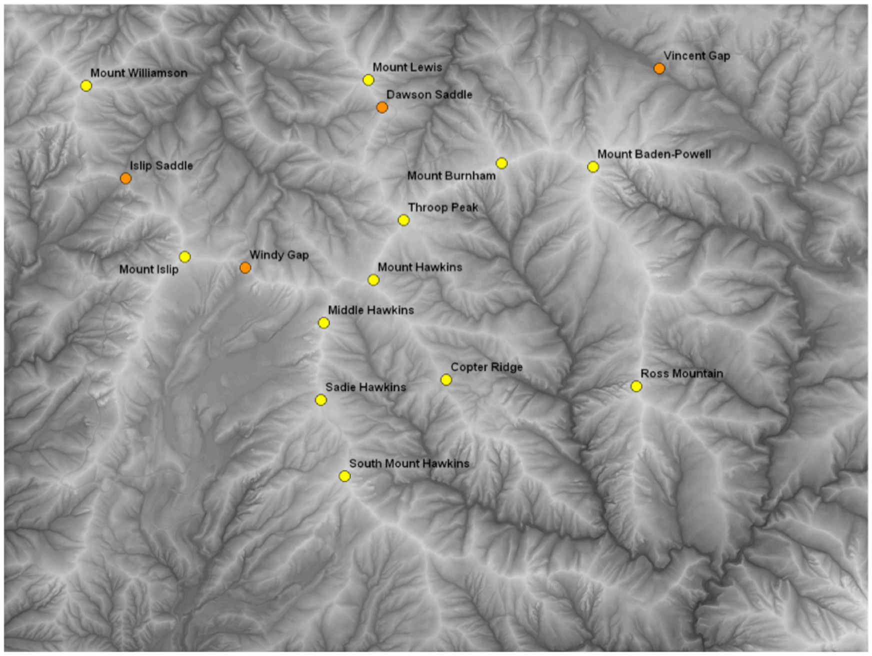
Incidentally, this scale invariance property can also be applied to generalization of standard hillshading, which is a project I'm working on and hope to complete in the near future.

Hillshading Again for Comparison



For comparison, here's the standard hillshading again for the same region. It should be clear that the two techniques present the terrain information very differently.

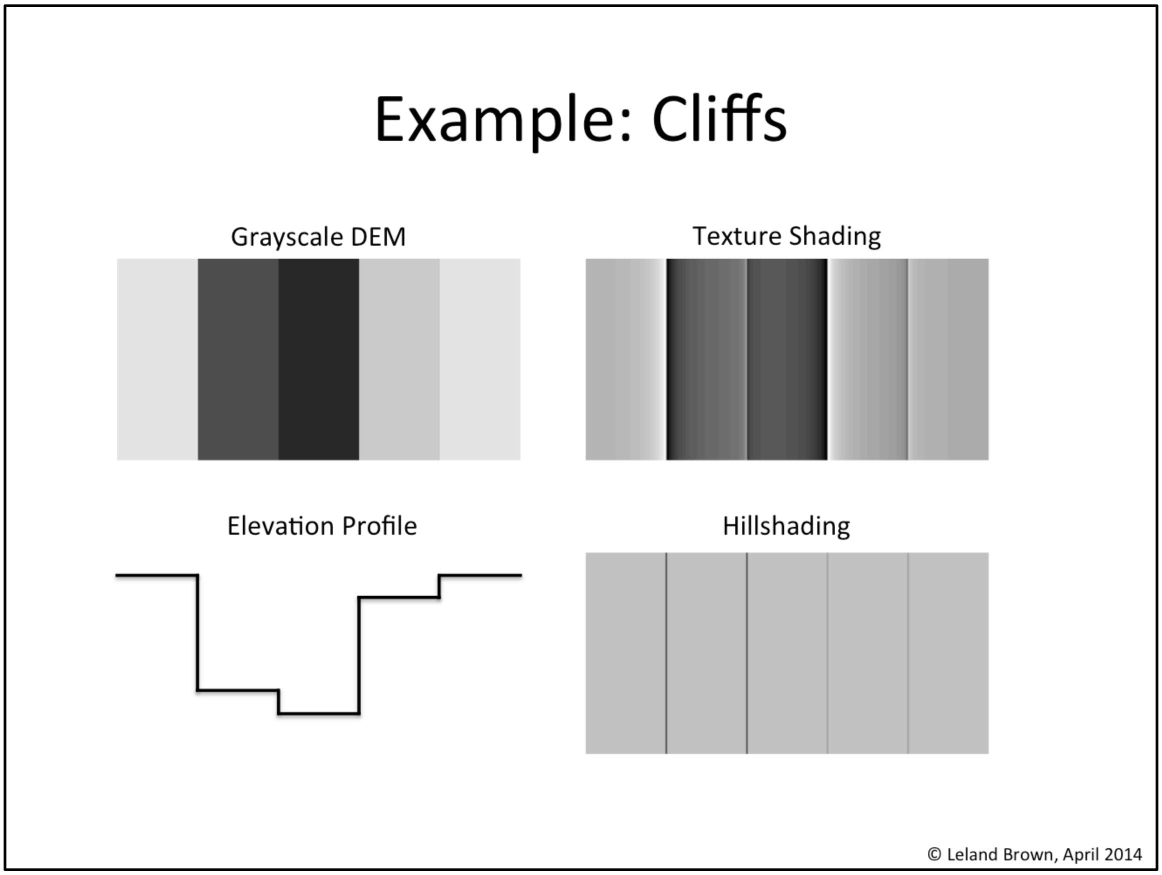
Result: Peak Map with Network Structure



San Gabriel Mountains, CA, USA Scale: 15 km x 11 km Data Credit: LAR-IAC/Infotech via USGS

Returning to my original goal of better supporting a mental map of my local mountains, here's another portion of the San Gabriel Mountains. I've marked the named peaks with yellow dots and the named saddle points with orange dots. I think it's clear now on this map how these are connected by a network of ridges. The drainage network is also clear. A visual hierarchy is apparent, with the major canyons and ridges most prominent, but the lesser ones also visible. This closely matches the structure of the mental map that I've now constructed for this area.

This work actually proved its value one day by saving me from getting lost on a hike. After working on these maps for a long time, I had learned much of the structure of the region shown here. On one hike I got separated from my group and started down an informal trail down the wrong ridge, where I was rapidly losing elevation (that I would need to climb back up) and heading deeper into the wilderness late in the day. From the knowledge I had gained from these maps, I was able to quickly identify the surrounding terrain, determine where I was and where the cars were parked, and realize that the trail I was on could not get to my destination. I was able to "rescue" myself before my situation got more desperate.

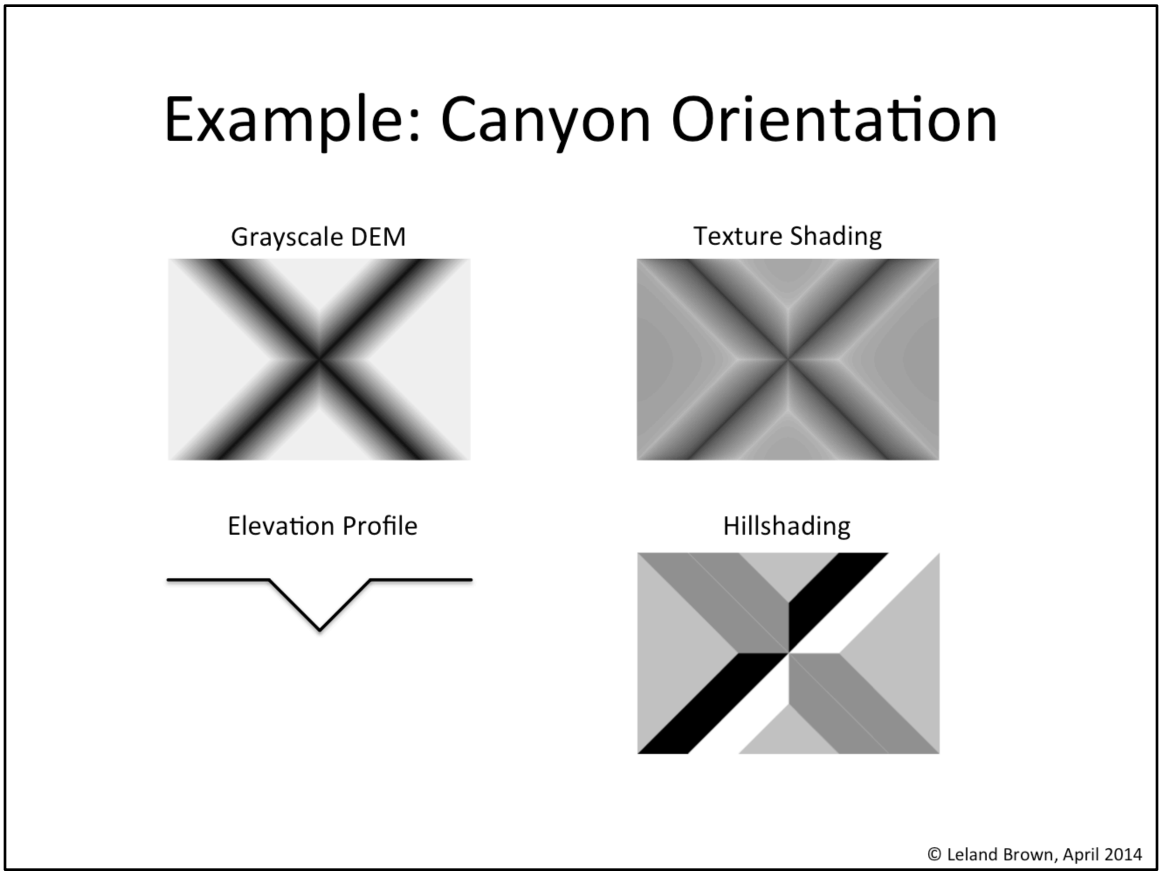


I have a couple examples using artificial, simplified terrain structures, to highlight the effects of texture shading and traditional hillshading on specific terrain features.

Here's a terrain consisting of a series of plateaus or terraces, separated by vertical cliffs of various heights. On the left you can see the DEM and the corresponding elevation profile. The DEM consists of bands of gray, each of a constant shade.

What texture shading does is to accentuate the boundaries between the bands (the cliffs). It ensures that there's a sharp difference in lightness across each of the cliffs. This accounts for the light and dark fringes on either side of each transition. (Without these fringes, you'd have the DEM image on the left.) The high and low cliffs can be distinguished by more and less dramatic shading transitions at the boundaries.

With hillshading, on the other hand, most of the pixels are colored a constant shade of gray, since they're all on a constant, flat slope – with the exception of the cliffs, which are only a single pixel wide. The high and low cliffs are indistinguishable, since they have the same slope. In addition, the cliffs on the right are harder to distinguish because they're illuminated (assuming lighting from the left). Adding shadows would help with the cliffs on the left, but not those on the right.



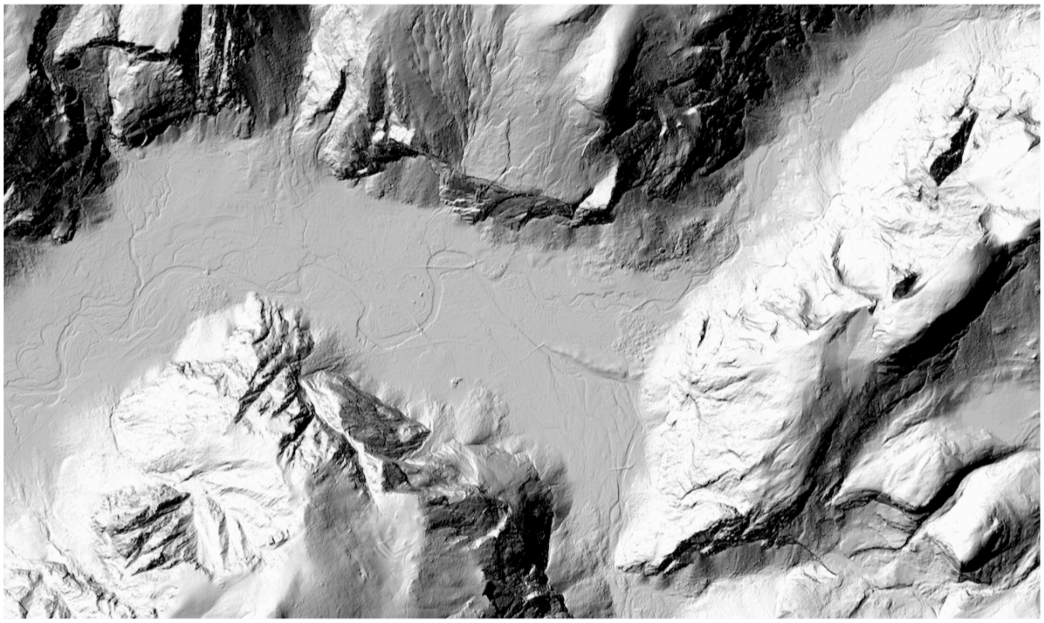
Here's an another contrived example, showing two intersection canyons, as shown in the DEM on the left.

I find the texture shaded rendering quite intuitive to interpret. (For some reason it makes me think of the corner between four pieces of a chocolate bar.)

In the hillshaded image, one canyon is aligned parallel to the lighting direection, and the other perpendicular. Besides the fact that the two canyons appear very differently, I find it hard to see a three-dimensional effect in this hillshaded image.

It has been argued that traditional hillshading is more intuitive for an untrained user to understand than texture shading. While I agree in general, we can see in this situation that there are counterexamples as well.

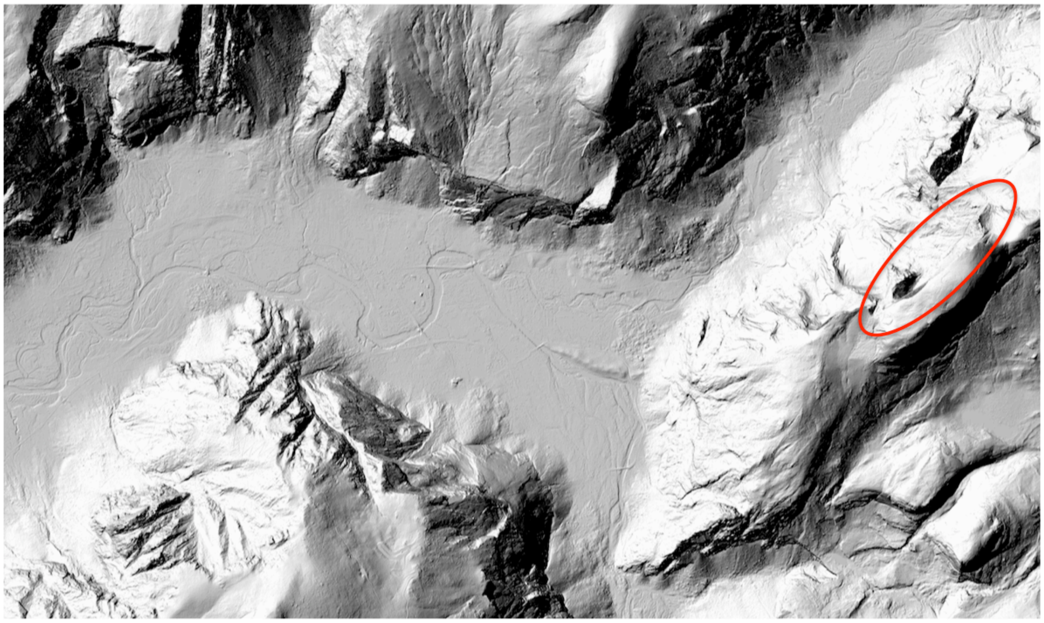
Yosemite Valley (Hillshading):
Where is the vertical face of Half Dome?



Eastern Yosemite Valley, CA, USA   Scale: 6.8 km x 4.0 km   Data Credit: U.S. National Park Service

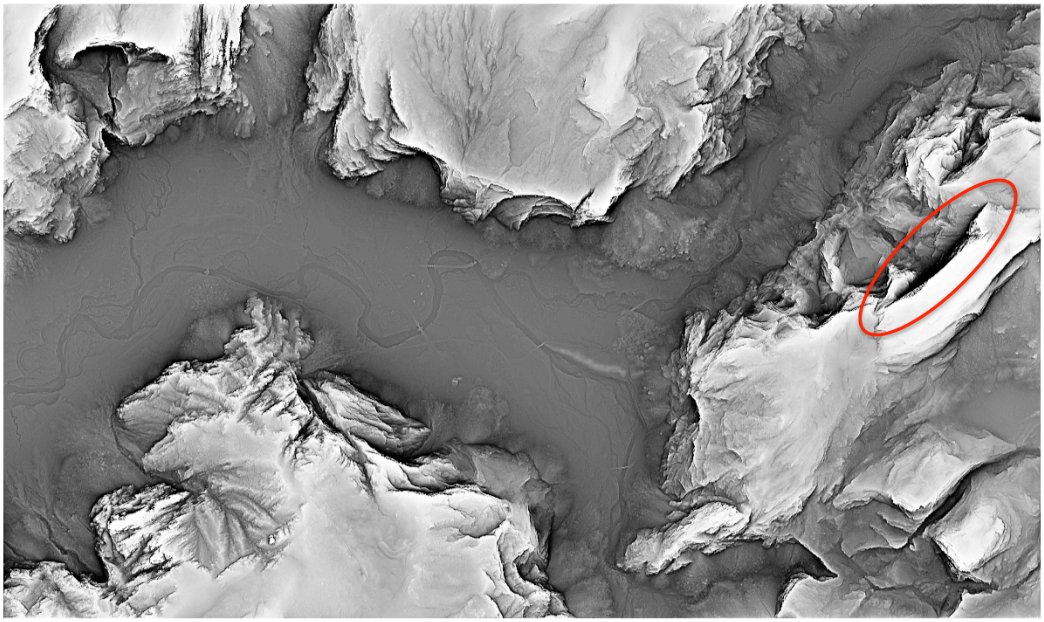
This is a hillshaded map of upper Yosemite Valley. A very prominent feature in the terrain here is Half Dome, a very large granite structure with a sheer vertical face over 1000 meters high. In this image, the face of Half Dome is very hard to find. Can you see it?

Yosemite Valley (Hillshading): Where is the vertical face of Half Dome?



The face of Half Dome is inside the red oval shown. In this projection the cliff is facing almost directly toward the hillshading light source, so that it's illuminated nearly the same as the horizontal top of the dome, making the cliff almost invisible.

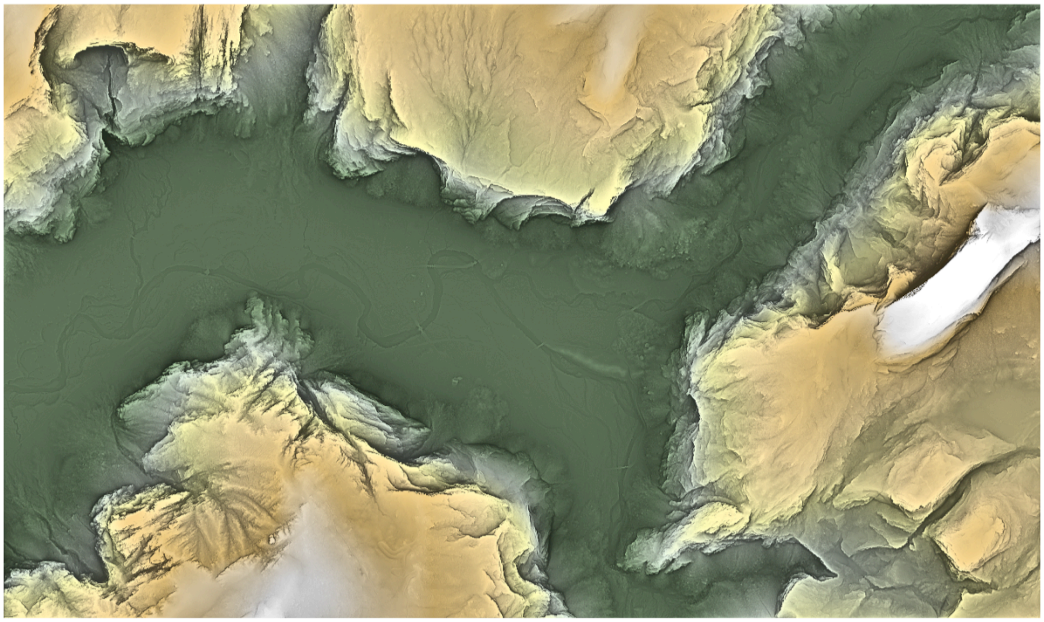
Yosemite Valley (Texture Shading)



In contrast, texture shading always guarantees that there is a strong light-to-dark transition at any cliff, especially such a large one; so the face of Half Dome is easily seen.

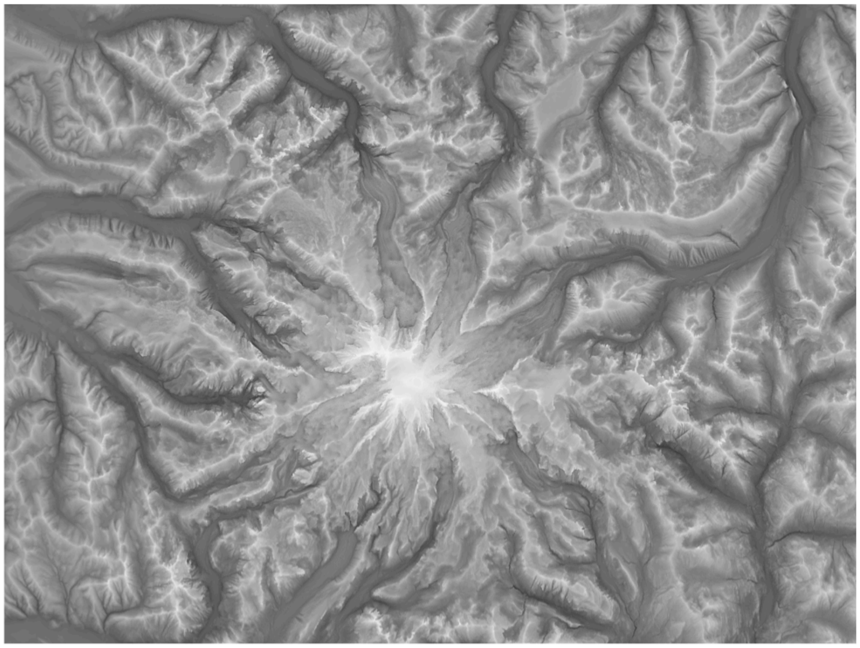
Notice also the detail that's visible along the river in the valley – the banks of the river and the bridges crossing the river. Thus although texture shading keeps the details subdued in order to maintain visual hierarchy, in this case it's still capable of making features visible across a very high dynamic range – from the 1000-meter cliffs to the river banks which are only a few meters high.

Yosemite Valley (Texture Shading + Color)



Here is the same image but with hypsometric tints added. The colors, of course, are based on the absolute elevations from the original DEM.

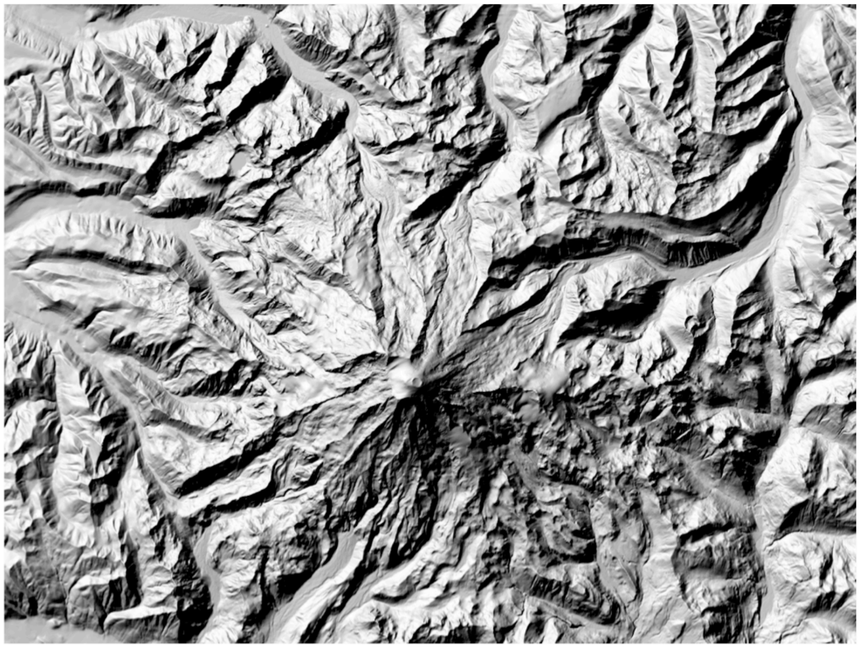
Mt. Rainier (Texture Shading)



Mt. Rainier, WA, USA Scale: 37 km x 28 km Data Credit: NED

While texture shading seems to work very well for mountains like the San Gabriels, which I had in mind as I developed the idea, I've found there are other types of terrain for which it doesn't work as well. The clearest example is volcanic cones, such as Mt. Rainier, shown here. While the canyons around the peak are clear, the cone of the mountain looks very flat to me in this image – I don't see a three dimensional effect at all.

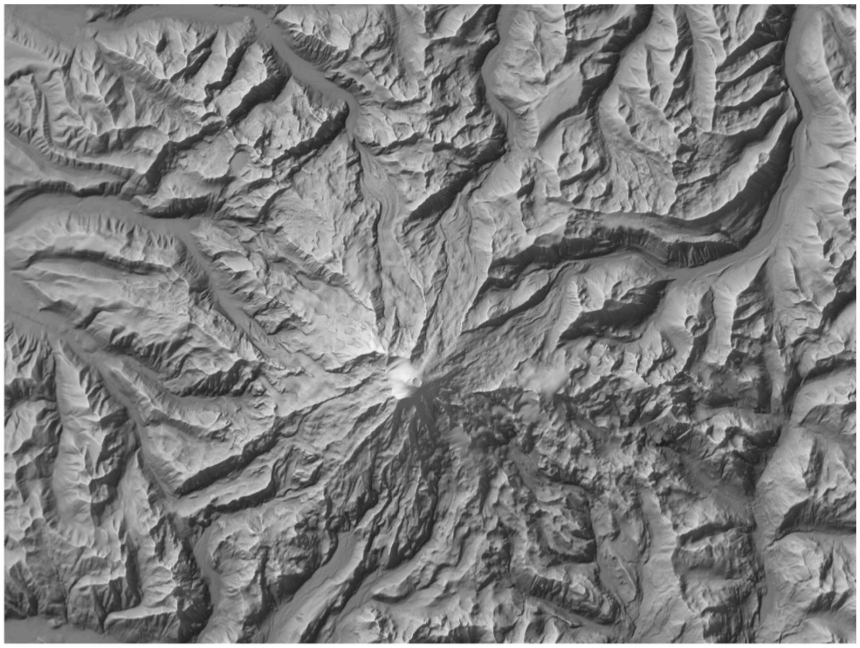
Mt. Rainier (Hillshading)



On the other hand, hillshading produces a nice three dimensional effect for Mt. Rainier.

Taking some wise advice from Tom Patterson, we can blend the two techniques …

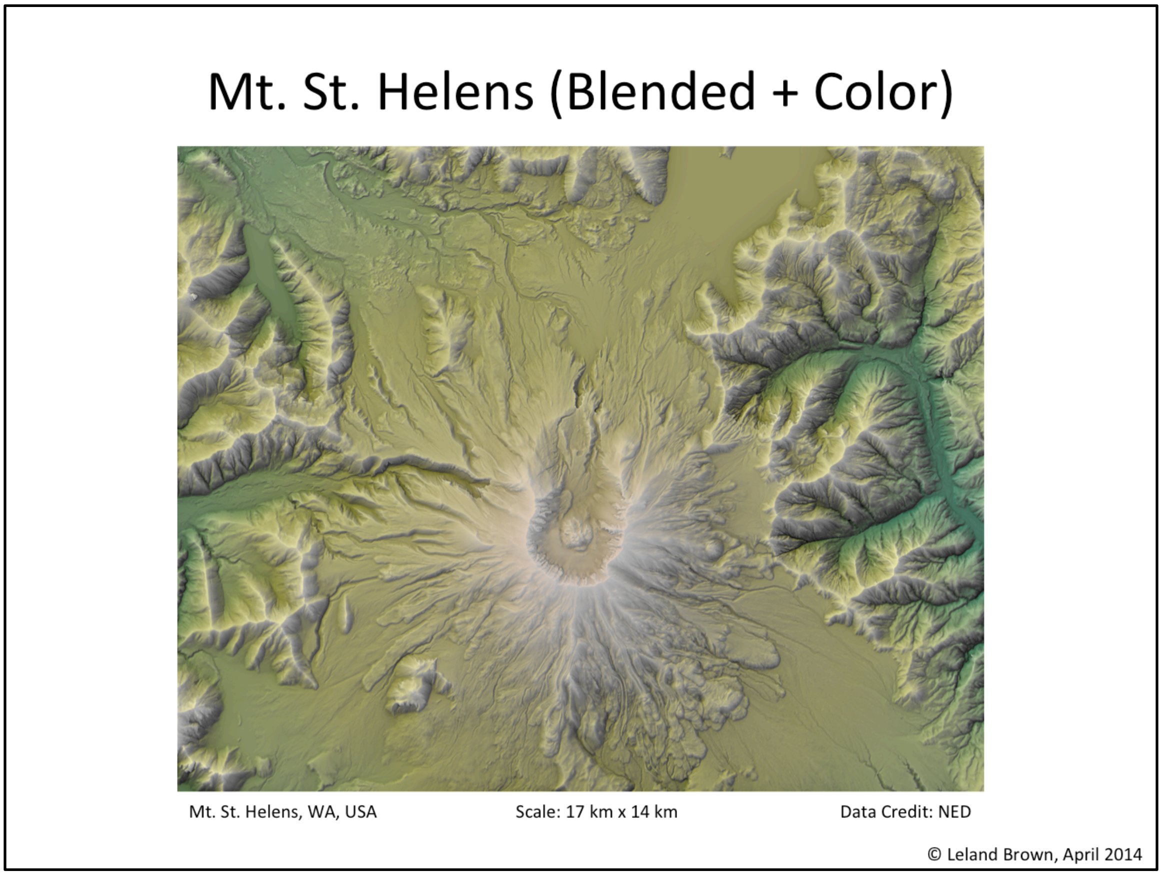
Mt. Rainier (Blended)



Here is the Mt. Rainier area rendered using a combination of texture shading and standard hillshading. It retains most of the best qualities of each, enhancing the canyon drainage structure and also giving a three dimensional effect to the volcanic cone.

This parallels an observation made by Patrick Kennelly regarding his sky models technique, that models with a directional component better convey the three-dimensional appearance of certain relief. (See his paper with James Stewart at http://myweb.cwpost.liu.edu/pkennell/reprints/peer-reviewed/GeneralSkyModels.pdf.)

While this is not one of my favorite images, I'm really pleased with the results from another volcano …



This image is generated by blending texture shading and hillshading for Mt. St. Helens, and once again adding hypsometric tinting. Here the two shading techniques are merged using a simple transparency effect, with 70% texture shading and 30% hillshading. The results seems to preserve the best qualities of each.

When I began this project, I viewed the orientation dependence of hillshading as a problem, and isotropic techniques as a better alternative. After gaining some experience, however, I've now come to see that terrain representation benefits most from combining a directional component, such as hillshading, with an isotropic component, such as texture shading. The problem is not that we've been using the wrong one, but that our maps have been incomplete; both pieces are needed in order to see the whole picture.

Future Work

- Add nonlinear brightness adjustment for texture shading
  - Analogous to the nonlinear contrast adjustment currently included
  - Helps to soften the light on the ridgetops to appear more realistic
- Apply scale invariance concept to traditional hillshading
  - Significant progress on this already
  - Allows blended images to retain multi-scale visual hierarchy
- Adapt contrast locally to ruggedness of terrain
  - Better displays terrain containing both rugged and flat areas
  - Reduces need to tune detail and contrast settings for each map
  - Goal is to accomplish this in a way that preserves scale invariance

These are some ideas I'm currently working on for the future. The first two have been prototyped and are nearly working. The third is a harder problem, but I believe I have some ideas toward a solution. I'm grateful to James Meacham for his feedback that provided the inspiration for the first idea on this list.

Resources

- For more information see:
  - www.textureshading.com (this page links to the others)
  - box.com/textureshading
  - www.naturalgfx.com/tts.htm (user-friendly software for Mac)
- Includes:
  - Mathematical details
  - More examples
  - Software to render texture shading (Mac, Windows, source code)

The first website listed here, textureshading.com, contains links to the other sites.

The box.com site contains my original 2010 presentation at NACIS, which includes more detail on the mathematics, and many more examples of texture shading (from an earlier version of the algorithm). There is also an open-source, cross-platform software program to do the rendering, using a command-line interface.

The third site has a program for the Mac written by Brett Casebolt of Natural Graphics. It implements the exact same algorithm, but provides a graphical user interface, quick preview window, numerous input and output file types, and several other features, making texture shading much easier to use.

Please feel free to contact me with any problems, suggestions, or other feedback you have. If you don't have my personal email address, I can be contacted through the box.com site by registering for a free account.