

How to Become a Mad Scientist, in Two Easy Steps

by Larry Ames, Dec. 1, 2014 [updated 10/7/15]

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The following is adapted from a talk I gave at the Lockheed Martin (LM) Advanced Technology Center (ATC) Colloquium in Palo Alto, California, on March 20, 2014, at the end of my 30-year career there as “Senior Staff Physicist” (aka, “Mad Scientist”).

It's actually pretty straightforward to become a Mad Scientist:

1: become a scientist.

2: go mad.

Note: the sequence is important: if you go mad first, it's hard to study science.

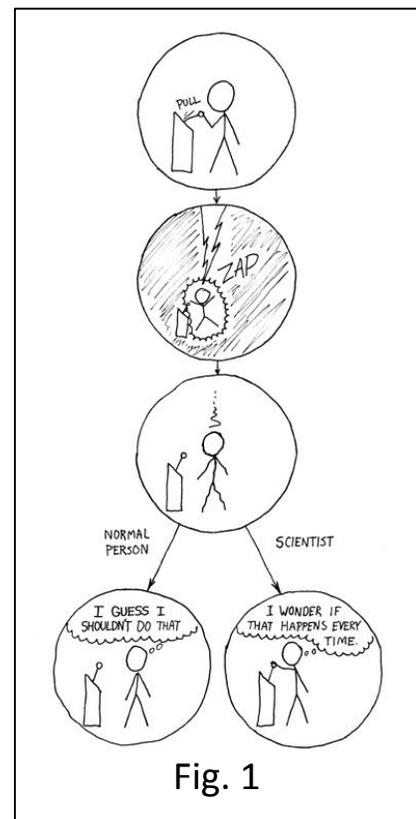
Step 1: Become a Scientist

First, let me discuss becoming a scientist. I'll relate some old sayings, talk about Sherlock Holmes and llamas, and try to make everything obvious.

Figure 1 is cartoon from xkcd.com that does an excellent job of illustrating how the scientist's mind-set differs from that of a normal person: any reasonable person, if shocked by pulling some lever, would decide that he or she shouldn't do that, whereas the scientist wonders if that happens every time.

Figure 2 is my resume – my formal training as a scientist.

- My Ph.D. thesis topic was, shall we say, “esoteric”. I was basically doing “alchemy” – elemental transmutation: the changing of carbon into oxygen. (Okay, the big money has always been in turning lead into gold. I think only 6 people in the world were interested in what I did, but it did show the world that I could do research, and it also got me those three letters at the end of my name...)
- My Masters topic was far more prosaic. While I was an undergrad at the University of Arizona, one summer I did an Honors Project measuring various coatings that were being considered for use in solar water heaters. (It turns out that "Rustoleum BarBQue Black was better than most of the fancy optical coatings tested.) Then, as a grad student at the University of Wisconsin, I was allowed to submit my U.of A. paper in lieu of a thesis project, and so technically it became my Masters thesis.



The University of Wisconsin in Madison provided a very practical education. Students in Experimental Nuclear Physics were expected to not only conceive of their experiments, but also to build them. And that meant more than simply drawing up some sketches or diagrams: at the U.of W., one was expected to actually make them. They had a computer that the students had to wire up by hand, connecting each electronics box to the appropriate input. The students had to write their own software (and I found that the algorithms we used for fitting nuclear resonances would prove especially useful later on). The students had to make their own electronics: they had an instructor to teach soldering and how to use op-amps, but you built your own electronics. And the University had a machine shop and an instructor that taught us how to use a drill-press and a metal lathe to make our own experimental apparatuses. I learned how to actually make things, and, for the rest of my career, when I designed something, I would do it in a manner such that I could make it myself if I had to. And that meant that the designs were straightforward and relatively easy to build, which in turn made them more affordable and easier to be produced on schedule.

And one more point about my resume: the company hired me by mistake. After I'd been working there for five years or so, I was asked to interview some potential new hires. I recommended a couple Ph.D.'s in physics, but was told that the company wouldn't hire them, as they didn't have a degree in Optics. I said, "well, what about me?", and they said I had that Masters from the University of Arizona in Infrared Metrology – that summer paper on water heaters(!). I replied, "Yes, yes I do", and I haven't mentioned it again until I gave this talk.

Figure 3 lists a number of the projects I worked on over my career. Don't worry about the acronyms: most people in aerospace talk in TLAs (Three Letter Acronyms), but not even they know what all of them actually mean. (And the program names are not all that important to this talk.)

What is of interest is that most of these projects were canceled, not funded, or otherwise not selected. Somewhat discouraging! However, projects can be lost or canceled for a variety of reasons, including the end of the Cold War, a change of power in Congress, or a change of mind by the customer – it's not your fault. Also, even if a project is canceled, it can still set the groundwork for a future win.

Nonetheless, it's nice to have something more to show for your time on the planet than a shelf of notebooks documenting canceled projects. I have spent my spare time on various neighborhood civic projects: attending meetings to promote a bike-trail here or preserve a historic structure there (see Fig. 4). I might not be able to point to a satellite in orbit, but I can point to a several acre park on the Los Gatos Creek.

- B.S., Math & Physics, University of Arizona (Tucson), 1972
- M.S., Physics (thesis: "Infrared Emissivity of Optically Thin Films"), 1974
- Ph.D., Experimental Nuclear Physics (thesis: "Natural Parity Levels in Oxygen-16"), University of Wisconsin (Madison), 1979

Fig. 2

- Star Wars (BSTS, etc.)
- Cel-Star
- CNC Accurization
- Object Pose Measurement System
- Zenith Star
- Air Bearing Test Facility
- Gunship Ballistic Wind
- Continental Drift Metrology
- HIRDLS
- Triana
- Space Interferometry Mission (SIM)
- Terrestrial Planet Finder (TPF)
- BA4
- SP

Fig. 3

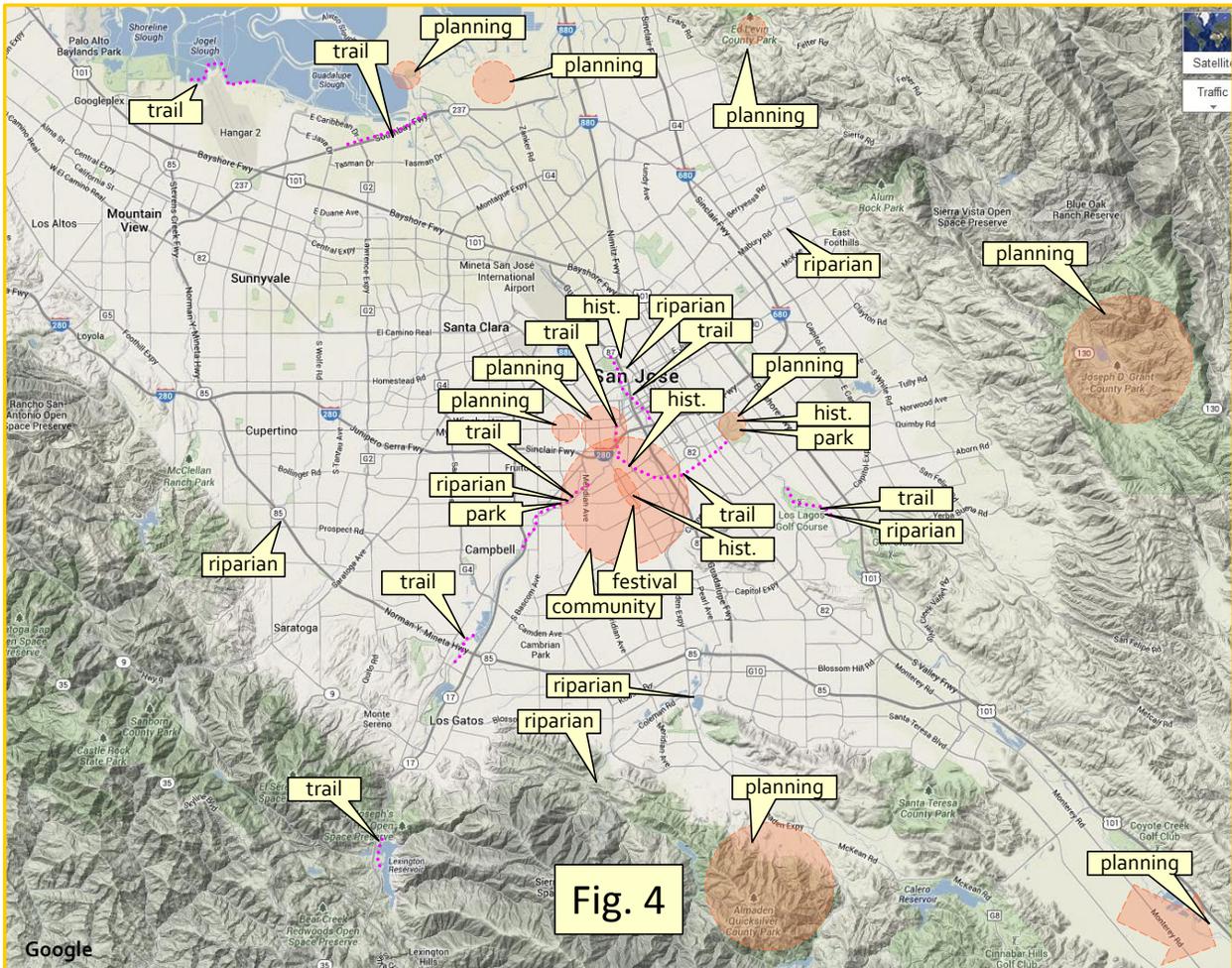


Fig. 4

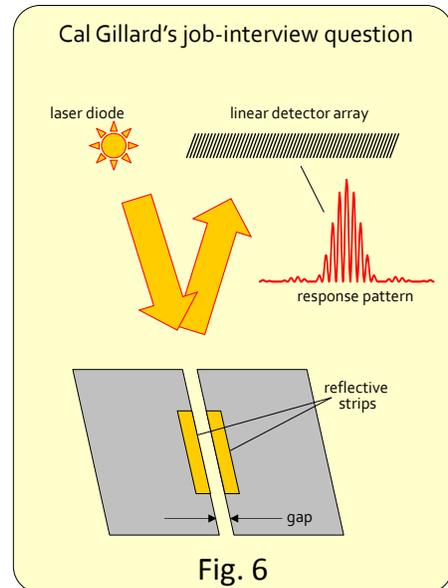
Also, to keep things interesting (and to try to avoid going mad), I made a point of learning something new on each project (see Fig. 5): I honed my skills with metrology on one project, learned how to program in C++ on another; I worked on electronics here and on optics there.

Let me go thru and describe some of the projects with a little detail. The first one (Fig. 6) is from before I even started at Lockheed Martin: it was from my hiring interview.

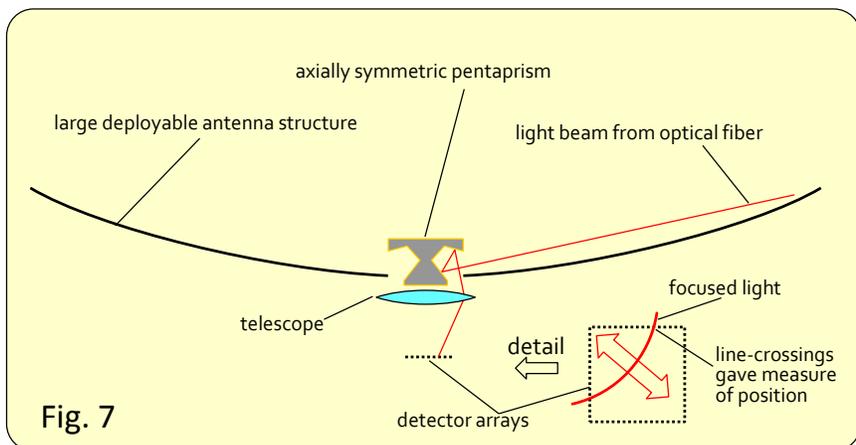
<ul style="list-style-type: none"> ■ Star Wars (BSTS, etc.) canceled ■ Cel-Star not funded ■ CNC Accurization ■ Object Pose Measurement System ■ Zenith Star ■ Air Bearing Test Facility ■ Gunship Ballistic Wind not bought ■ Continental Drift Metrology not selected ■ HIRDLS ■ Triana not launched ■ Space Interferometry Mission (SIM) canceled ■ Terrestrial Planet Finder (TPF) not funded ■ BA4 canceled ■ SP 	<table border="1"> <tr><td>metrology & algorithms</td></tr> <tr><td>communications & link equations</td></tr> <tr><td>data reduction</td></tr> <tr><td>metrology & algorithms</td></tr> <tr><td>mechanical design</td></tr> <tr><td>programming & control algorithms</td></tr> <tr><td>geometry & algorithms</td></tr> <tr><td>geometry & algorithms</td></tr> <tr><td>electronics & h/w - s/w I/F</td></tr> <tr><td>C++ software</td></tr> <tr><td>metrology & geometry</td></tr> <tr><td>metrology & geometry</td></tr> <tr><td>geometry: stray light</td></tr> <tr><td>stray light, optical distortion, calibration</td></tr> </table>	metrology & algorithms	communications & link equations	data reduction	metrology & algorithms	mechanical design	programming & control algorithms	geometry & algorithms	geometry & algorithms	electronics & h/w - s/w I/F	C++ software	metrology & geometry	metrology & geometry	geometry: stray light	stray light, optical distortion, calibration
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Fig. 5

One of the people interviewing me was Cal Gillard, who it turns out was then the resident Mad Scientist, and who later became my mentor. During the interview, he described a project he was working on: a “gap sensor” to measure the distance between adjacent components. The idea was that the edges of the components would be plated with narrow reflective stripes; laser light would reflect from them and create an interference pattern; and by detecting and then analyzing the frequency of the fringes, one could deduce the gap spacing. I instantly recognized this as a “Young’s Double Slit”, and I describe how I could adapt the software I’d used on nuclear resonances to fit the pattern, and I bet I could also get the phase of the fringe pattern that would give the relative “piston” position as well as the gap spacing. I received a firm job offer before I’d made it home that evening!



Cal Gillard liked to dream big! At the time when cell phones were first being developed, he proposed “Cel-Star” (Fig. 7) – a method of operating *all the cell phones in the world* from just three giant satellites in geosynchronous orbit. Each of these satellites



would unfurl to deploy an antenna over 100 feet in diameter, with graphite-epoxy ribs mounted to a central hub. The magic that would make this possible was his idea for an “axially symmetric pentaprism”, basically an aligned pair of mirrored cones. There were to be optical fibers mounted to the ribs, and light would shine back to the pentaprism and be reflected into a small optical telescope: the position of the image would then be used to control the position of the ribs and thus the figure of the antenna, thereby assuring a proper focus of the signal by the satellite. Cal and I would give presentations on the concept to the various levels of management, and we almost evolved into a comedy act. Cal was quite the visionary, but he would have trouble explaining things to normal folks: things would be obvious to him (especially after he had worked on them for months) and so he would skip over steps when trying to present his ideas. I would be up on stage with him, and I would see the audience’s eyes glaze over in confusion. I’d stop Cal, explain what he was trying to say, and get the audience back up to speed. Cal would then say his next sentence, and I’d pause him and explain what he’d said, and so forth: I was basically his “translator”! The company never did buy his idea: there was a rival proposal for a swarm of low-orbit satellites (the Iridium system), and management banked on getting more revenue by launching a bunch of someone else’s satellites rather than taking the risk trying to build something that large ourselves.

Project OPMS – the Object Pose Measurement System (Fig. 8). Lockheed Martin had a “test chamber” (actually, a giant room) in which various objects to test were hung from strings. They wanted to be able

to know the precise position and orientation (the “pose”) of the object without touching it. It’s rather straightforward to place a couple reflective targets on the object and look at them with cameras from several viewpoints – a simple “robotic vision” if you will. All you need are the locations of the cameras, and the rest is basic geometry. But the problem was that the cameras were not accessible: they were behind protective walls, and so it was not feasible to measure their positions relative to one-another with sufficient accuracy.

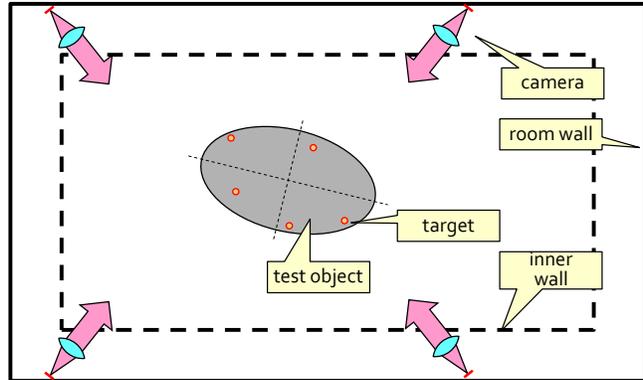


Fig. 8

Solution: have the cameras view a simple target – a sphere, such as a reflective ping pong ball. All the cameras could see it at the same time. You don’t need to know where the ball is, but you do know that all the cameras will have to agree on the position. Repeat the measurement with the ball in different locations, and a variant of that nuclear resonance-fitting algorithm would be able to least-squares-fit to find the relative positions of the cameras.

Slight problem: how do you get reflective paint on a ping pong ball? If you try wrapping it with reflective tape, it would wrinkle and bulge out here and there, giving a false centroid that would mess up the measurements. Solution: use reflective paint, like that used by the highway department on roadways.

So, have you ever thought about why the road paint is reflective? My summer job in high school was with the State Highway Department, helping to paint those stripes on the road, so I knew the answer: it’s just ordinary paint, but it is sprinkled with glass beads before it dries. Each glass bead is embedded in the paint and acts like a cat-eye, focusing the incident light on the back glass/paint interface (Fig. 9) and then focusing the scattered light back towards the source. The Highway Department buys glass beads by the 50-lb. bag and we just needed a tablespoonful, so I called up CalTrans and asked if they could give us some. The stuff worked great and the test chamber was properly calibrated. And the folks at CalTrans got quite a kick out the fact that they got to help Lockheed Martin with the space program!

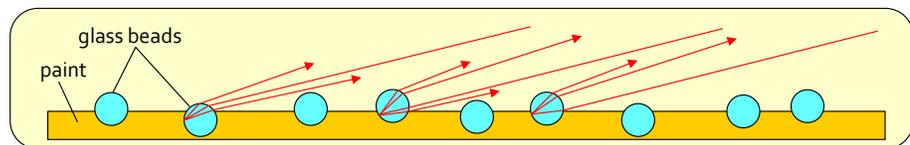


Fig. 9

The Air Bearing Test Facility.

I wrote the software for a small test facility in Palo Alto, and after half a year, it was ready for a major demonstration before some company vice-president. I spent days beforehand making sure everything was working, and all was perfect. Come the day of the demo, it Just Would Not Work – every time I tried running the code, it would crash the computer. (I finally ended up doing a “song and dance” using diagrams and screen-shots.) It took a week or two to discover the problem: I had somehow dimensioned a field to display the day’s date using only three digits, and the demo was Oct. 10th – the first time in over half a year that would require four digits to display the month and day, and that 4th digit was then somehow dumped in the operating system’s memory and would cause the computer to crash. This was a few years before the dreaded Y2K bug was supposed to hit: my demo was an early casualty! (And, on Jan 1st, 2000, while the world didn’t come crashing to an end, I do recall seeing the date displayed some places as “Jan. 1, 19910”...)

The Gunship Ballistic Winds (GBW) Program.

The Air Force has a couple gunships – C-130's that are modified to carry guns that fire big shells. But even these large shells can be blown off-course by the wind; and the wind often goes in different directions in different layers of the atmosphere.

Normal operation: fly in over target, shoot a couple shells, see where they land, and then zero in on the target.

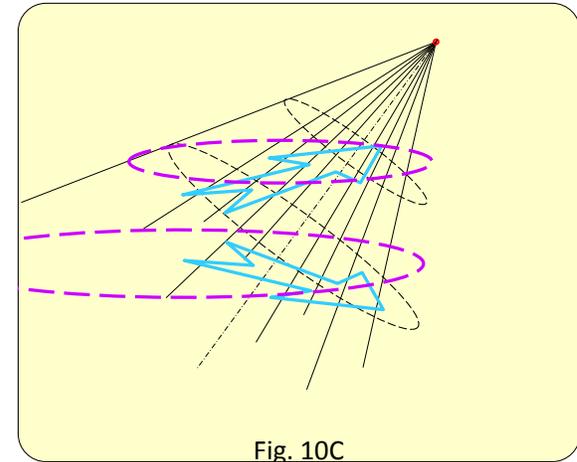
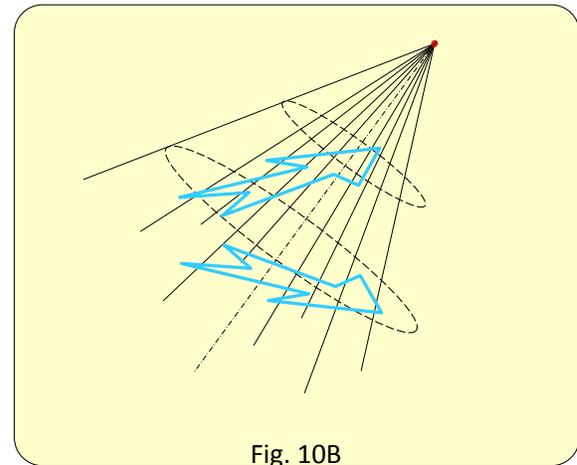
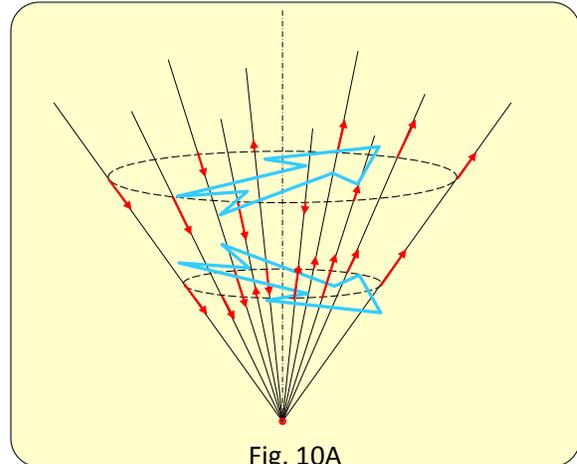
Problems: (a) you have to spend extra time over the target while the bad guys are shooting at you, and (b) the first couple shells could land somewhere you don't want them to go.

It'd be nice to quickly measure the wind profile as a function of altitude as you're flying in so that the aim-point could be adjusted to compensate for all the various cross-currents.

Enter LADAR – Laser Radar. The state-of-the-art at the time involved a unit placed on the ground, with a conically scanned laser beam. Light reflects off of dust particles in the atmosphere; time-of-flight gives the distance to the dust, the Doppler-shift in the return signal gives the relative line-of-sight (LOS) velocity, and an angle encoder gives the direction. The wind at a given altitude could be determined by fitting a sine curve thru the angle-encoded range-gated data (Fig. 10A).

But you can't just go and place a laser radar unit at the center of hostile territory: you need to measure from the air. Furthermore, you'll be looking down at some angle, from a moving airplane: if you do the standard range-gating (Fig. 10B), you'll be sampling winds in different layers going in different directions. LM hired some consultants who explained that this was a problem, and said that it couldn't be done.

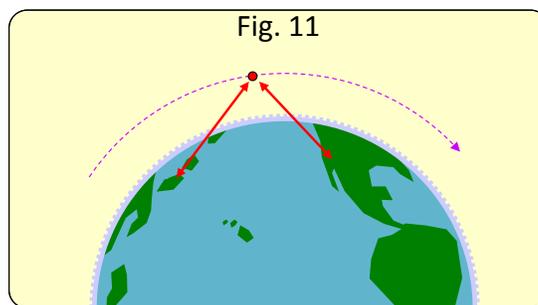
A true mad scientist doesn't like to be told that something can't be done, and so within, oh, maybe 10 seconds, I had come up with a solution. It took an hour to explain it to the audience, a year to actually code, build, and demonstrate the solution, and three years to get it patented, but it still seems obvious: vary the range-gating as a function of angle so that the same atmospheric layer is sampled (Fig. 10C). Works perfectly! "Okay, you invented it, you get to name it", and since this is in effect matching the altitude by using ellipses, this became the Altitude-Matching



Elliptical Scan algorithm. And, since the aerospace industry does everything by T- or FLAs, this became the A.M.E.S. algorithm, and so I got a patent on my name! (Not to be outdone, my co-worker Dave came up with a Digital-Analog Velocity Estimator circuit, so the AMES algorithm used the DAVE circuit.) We built and successfully demonstrated the system, but nonetheless the customer decided not to buy it.

Another GBW story: midway thru the project we had a major customer review: an all-day presentation where we discussed all details of the project before a group of Air Force officers. I am assigned to discuss error-analysis – one of the most boring and detailed-oriented aspects of the project – and I’m to do it immediately after lunch: good luck keeping that audience awake! By chance a week before, my youngest son, then age 4 or 5, had given me a “model airplane” he’d made at daycare made out of a 2x2 and some short planks of wood: I used that toy plane as a prop in my presentation while I illustrated the various angles and uncertainties. Immediately after the talk, my manager chewed me out, saying that it was “very unprofessional” and not at all “in the company style”. But at the end of the day, the customer gave their evaluation and said that my talk was the best they’d ever heard and now they finally understood the various details of the program. My manager then had to come by my cube and eat crow. I’ve kept that model plane hanging from my office cube ever since, as a reminder that management isn’t always right, and sometimes using a simple model is best.

Not every project is a multi-year endeavor: the following was a two-week proposal effort. It turns out that there is (or at least, was) a satellite in orbit that was basically a disco-ball: a small sphere just covered with retro-reflecting mirrors. There’s a facility in California that would bounce pulsed laser beams off that satellite, measuring the time-of-flight to determine the distance, and a comparable facility in Japan also making those measurements (Fig. 11). They weren’t trying to measure the satellite, but rather the relative distances between the facilities: they were



measuring Continental Drift! They were able to measure motions of a couple millimeters per year, but they wanted even better resolution. The incumbent vendor was up for renewal, and LM decided to submit a proposal to try to take the business away from our rival. The customer was considering using a second laser at a different wavelength (color) to better measure and compensate for atmospheric effects. My analysis seemed to indicate that there was a 3rd-order effect that might negate the advantages of the 2-color laser, however I could more than compensate for that by curve-fitting – using that nuclear-resonance fitting algorithm again (!) Turns out the customer was happy with the incumbent and also wanted an excuse to buy a second set of lasers, and so we didn’t get the contract. Still, it was fun to contemplate the measurement of continental drift by means of an orbiting disco-ball!

Triana (Fig. 12): this was a proposal by then-Vice-President Al Gore for a low-cost satellite to be launched into the First LaGrangian Point, about a million miles closer to the sun than the earth. The satellite was basically a full-color camera that would always see the day lit side of the earth, and would see the entire day-lit hemisphere rather than just small patches of the surface like most low-orbit satellites do. And, instead of having the data collected by a small group for analysis and eventual publication, the data was to be posted immediately, real-time, on the internet, for all to use. It was derided by political wags as “the world’s most expensive screen saver”, but it could have been a powerful scientific tool, accessible by all. Even high-school students would have had access: think of the science projects it would have inspired, and how much more empowering (and probably cheaper) that

would have been than, say, operating the Blue Angels for flight shows. With a very limited budget, a group of us at LM built and tested the satellite. (I basically wrote nearly all the instrument software, although some (much?) was rewritten after a management dispute.) The satellite was built and delivered on time. However, the Presidential election had just taken place, Al Gore's opponent, "W.", was now in office, and one of the purposes of the satellite was to measure signs of Global Warming. "If you don't like the answer, don't ask the question", and so the satellite sat for years on a warehouse loading dock. (I understand that it has been retrieved from the dock, reconditioned, renamed, and repurposed, and may at some time actually be launched...)

[August 2015 update: The satellite was retrieved from storage, refurbished, renamed "DSCOVR", and launched. Figure 12a shows one of the first images: the full disk of the earth, with a view of the sun-lit backside of the moon as it crosses in between. Note how dark the moon appears: it actually is "charcoal gray" -- it only appears white when viewed against dark space. For more details, check out <http://www.nasa.gov/feature/goddard/from-a-million-miles-away-nasa-camera-shows-moon-crossing-face-of-earth>]

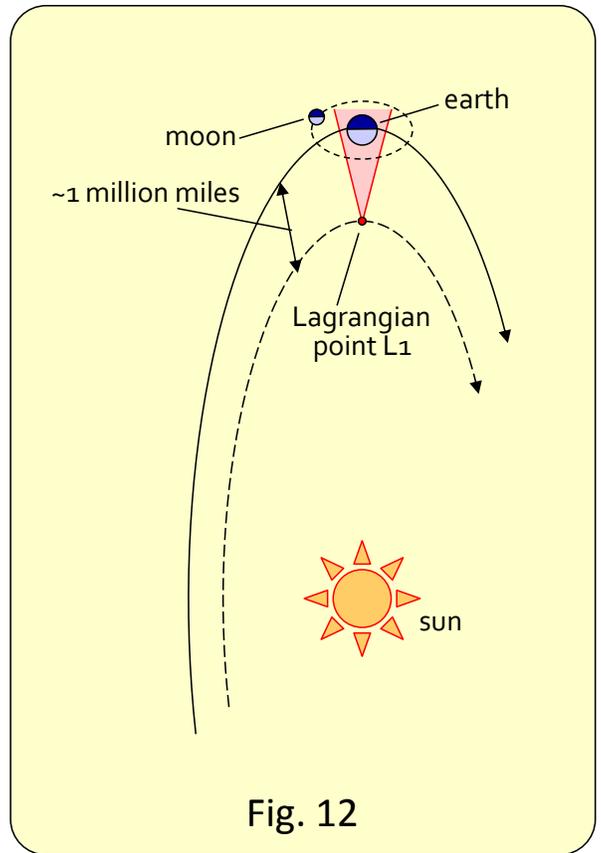


Fig. 12

SIM – the Space Interferometry Mission.

Have you ever wondered how they measure the distance to the stars? You can't just go out there with a tape measure... You've heard about the red-shift and how many light-years distant a star is, but how is that measured?

It turns out that only a relatively few stars can be measured directly, and that is done by means of parallax (Fig. 13). The star's position is noted relative to some very distant object, and then, six months later when the earth is at the opposite side of its orbit about the sun, the position of the star relative to the distant object is measured



Fig. 12a

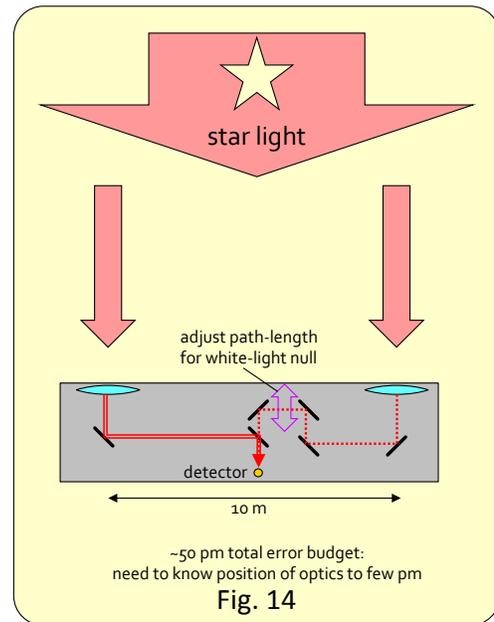
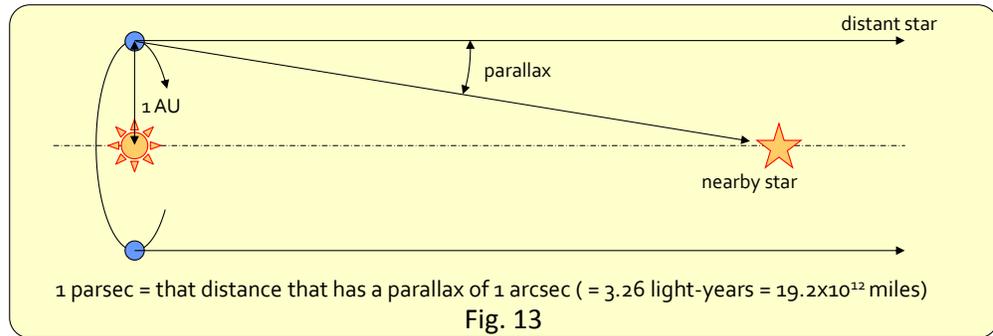
again. If the angle of parallax is one arc-second for the radius of the earth's orbit (i.e., 2 arc-sec for the orbit diameter 6 months later), the star is one "parsec" away, or about 3.26 light-years, or 19.2×10^{12} miles.

Telescopes can measure parallax down to about a hundredth of an arc-sec, allowing direct measurement of stars out to a few hundred light-years. Any distance beyond that involves extrapolations, estimates, and assumptions.

I'm not an astronomer and so I don't know the details, but there are some types of stars (identifiable by their spectral lines) that apparently all have the same brightness – at least that's true for those stars whose distances can be measured. *Assuming* that *all* stars of that type have the same brightness, those that appear dimmer must be further away: you've extended the "ruler" for measuring the stars by using that assumption. It takes something like seven different assumptions and extrapolations to get a ruler long enough to measure out to the edges of the universe.

The purpose of the SIM program was to build a satellite that could measure star parallax down to a micro-arc-second – ten thousand times better than before. This would enable the direct distance measurement of stars out to nearly a million parsecs, which would cover any star in our galaxy and a number of nearby galaxies as well, and it would eliminate any errors associated with the first several ruler-extending assumptions and extrapolations.

Figure 14 shows how SIM works: it involves a pair of telescopes at either end of a baseline: the length of the satellite (about 10 m). Light is collected by both telescopes from a given star, and the light is directed to the center where it is optically combined. The beam path has an adjustment, like the slide in a slide trombone. The path length is adjusted so that the distance from the star to the left telescope and then to the central combiner is exactly equal to the distance from the star to the right telescope and the mirror. When the path lengths are matched to better than a fraction of a wavelength of light, the starlight will interfere, as in an interferometer. While a second pair of telescopes is monitoring a guide star somewhere to hold the satellite steady, the telescope mirrors shift to look at a third star, the slide is adjusted to again get the interference, and the amount the slide was adjusted gives a measure of the angle between the third star and the first one.

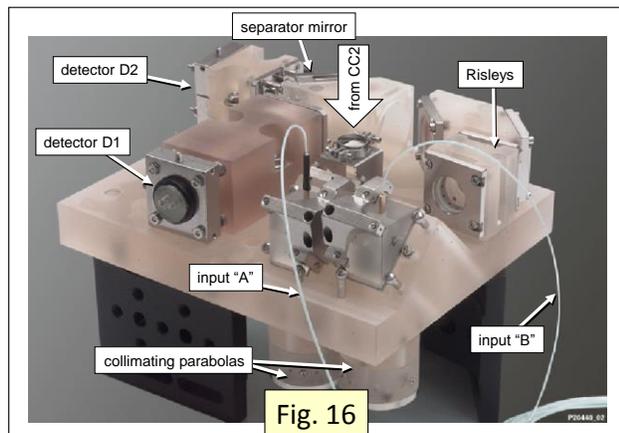
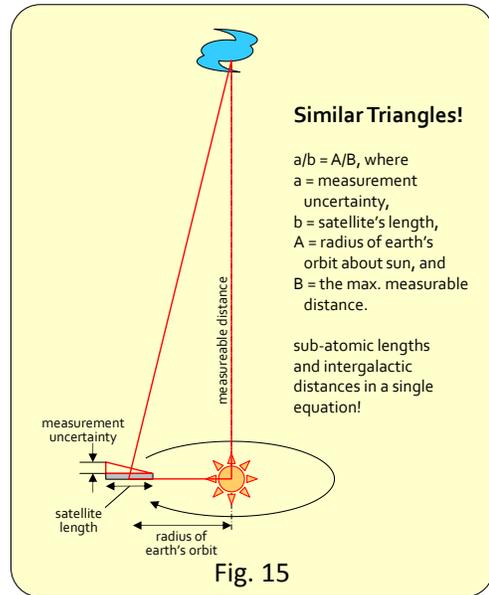


In order to precisely measure the stars, the relative positions of the telescopes have to be known, down to a couple picometers. It's basically "similar triangles" from geometry class (Fig. 15): "a" is to "b" as "A" is to "B": in this case, the uncertainty in telescope position (a small fraction of an atomic diameter) is to the length of the satellite (size of a bus) as the baseline of the measurement (the diameter of the earth's orbit about the sun) is to the measureable distance (to the nearby galaxies). Pause for a moment and think about that: how often you get to say "subatomic" and "intergalactic" in the same sentence?!

We developed a metrology truss comprised of about a dozen laser interferometers. These interferometers all had to be about three orders of magnitude more precise than any then available. This was a fun time: I got to fly down to Pasadena every other week for an afternoon of brainstorming at the white-board with physicists from JPL – the NASA Jet Propulsion Laboratory. We eventually designed and built the "QP" ("Quick Prototype") beam-launcher (the critical component in the interferometer – see Fig. 16), and we demonstrated 10 pm accuracy.

We at LM were working on designs for a new concept (called "the RT" beam-launcher) that would meet the 1 pm requirement, and we were just about to enter the development phase when the folks at JPL developed a case of "NIH" ("not invented here"). They too came up with a design for a new launcher, which they too called "RT", and we were instructed to

evaluate the two concepts as equal alternatives. Now, we couldn't call them RT-LM and RT-JPL, because that would "fan the flames of rivalry"; we couldn't call them RT-A and RT-B, because that would imply that a ranking had already taken place; likewise we couldn't call them RT-1 and RT-2 for the same reason. So, for the next year, we were working on RT-A and RT-1, and we worked to get the two designs to a comparable level of development so that they could be fairly compared. I mention all of this because a couple weeks later, the comedy TV show "Futurama" aired an episode involving parallel universes, and the characters were grappling with which was populated by "the evil twins": they eventually decided on the names "Universe A" and "Universe 1"! (In the end, the decision was to use the JPL design: it had "momentum" since the LM design had been ready a year before and so had been set aside. The overall program was curtailed shortly thereafter by some Congressional priority-setting process.)



Project TPF – the Terrestrial Planet Finder Project.

This was a NASA project to look for habitable planets orbiting nearby stars (!)

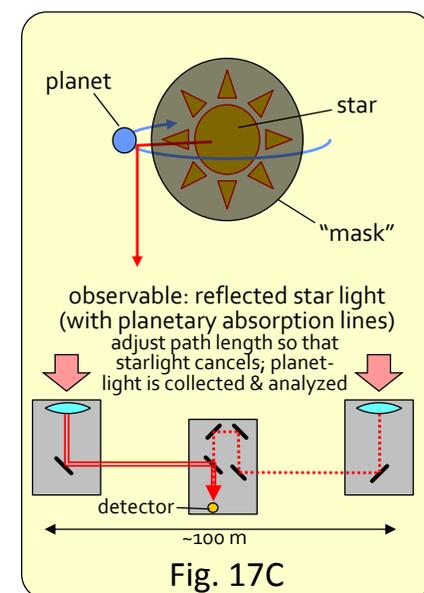
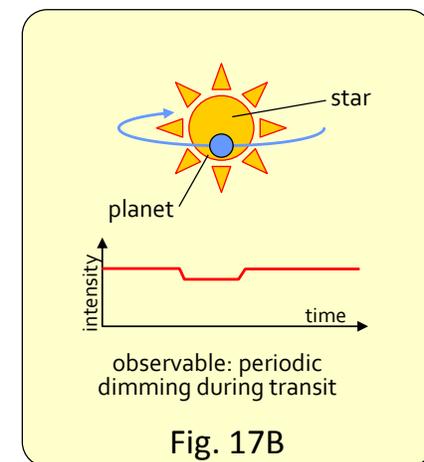
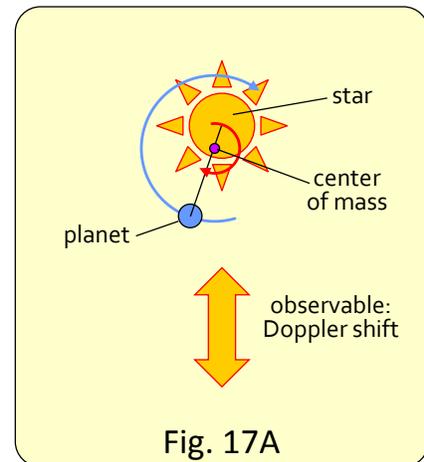
Over a thousand planets outside of our solar system have already been discovered, using two different techniques:

- A planet doesn't simply orbit about a fixed star: they both orbit about their common center-of-gravity (Fig. 17A), and if you watch the star very carefully, you'll see it move towards and away from you over the course of the planet's year. Astronomers at Lick Observatory above San Jose have been measuring the optical spectra of the various stars for several decades, and are able to detect the stars' relative motion from the Doppler shift in absorption lines. Over a hundred planets have been found by this method.
- Another method: look for "transits", where the planet crosses in front of the star – Fig. 17B. The Kepler satellite basically just stared into space for years, monitoring the brightness of a hundred thousand stars, and every so often, one star or another would dim for a short period of time as some planet crossed in front of it.

There is a third method for looking for stars, based on the concept for a coronagraph: if you can block out the light of the star, you might see the star's light scattered by a nearby planet (Fig. 17C). And, while the first two methods only indicate the presence of a planet, this third method can also tell if it might be habitable: the light reflected from the planet can be spectroscopically analyzed to see if there are absorption lines corresponding to oxygen, water, etc.

The TPF proposed to have a telescope on each of several satellites that were to fly in an array. These would collect light and send it to a central unit that would optically combine them, much like the SIM satellite. By carefully adjusting the beam path lengths, the starlight could be made to destructively interfere, and the star would vanish, leaving only the light reflected off of the nearby planets.

Again, this project was canceled when Congress changed NASA's funding priorities. Nonetheless, it was cool, something straight out of StarTrek: designing a deep-space array to look for Class M planets!



“LOTIS”, the Large Optical Test and Integration Site.

I needed to use a fairly large telescope, say, about 5 feet in diameter, to make some quick measurements at work. LM has some number of them around the site that within a couple months could have been set up for use. LM also had LOTIS, a giant test facility that had been built for a couple programs that later were canceled, but which at the time, while unused, was still being maintained.

LOTIS is humungous (Fig. 18): the telescope mirror is about 21 feet in diameter in a vacuum chamber that is the size of a modest two- or three-story office building (Fig. 19 shows me standing by the door). And the clean-room was just incredible: not a very-clean “class 10k” (i.e., 10,000 dust particles per cubic meter) or even “class 100”, it

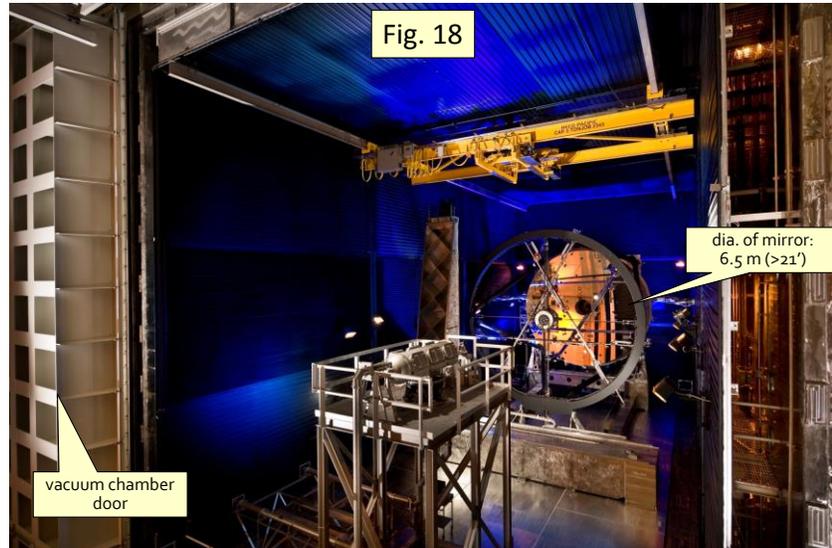
measured out at “class 2”! LOTIS had just undergone its routine calibration and testing, and was ready to use on a moment’s notice. It was complete overkill for what I needed, but it was available and could easily be adapted for my needs. It worked great! But very soon thereafter, it was decided to decommission the facility, and I understand the optics are now being shipped off somewhere for use in an observatory someplace. Thus, I am the only person ever to have actually used LOTIS for a real experiment.

Enough about work! Time to impart some of the “wisdom of the ages”!

My father had a couple favorite sayings. One was: “All elephants walk single file – at least the one I saw did.” The point was to not jump to conclusions based on a single observation. Investigate thoroughly, and collect a statistically significant amount of data.

Another of my father’s sayings: “I’ve never known paper not to take ink.” By that, he meant that just because it is written in a book somewhere, it doesn’t automatically mean it is true. And he passed away before the rise of the internet: the advice is even more relevant now!

And some folks treat anything generated by computer as gospel truth, forgetting about “GIGO” – “Garbage In, Garbage Out”. And even with the best of intentions, computers do not always give the right answer. I led an effort once to adapt some complex modeling software that had been years in development and that was maintained and operated by an entire group of dedicated programmers.



Give the code an estimate as a starting point and it would churn away and finally give an answer. We start poking at the code and find variables passed from subroutine to subroutine. Buried deep within the 100,000 lines of code was the statement “answer = user’s guess”, and that number was passed back up thru all the routines, modified slightly here and there, and then output as the answer. That line was probably stuck in there at some point for debugging, but who knows how long it had been there? But everybody had been happy: their guesses had been validated by the computer code, showing that they must be right! (Whenever I have to use some new code, I first try to break it: give it a range of inputs and see if the outputs are appropriate. Also, do “sanity checks”: are the answers of the right order-of-magnitude? Do they agree within expected tolerances with simple first-principles back-of-the-envelope estimates?)

My Major Professor at the Univ. of Wisconsin, Dr. Hugh T. Richards, would say “They won’t appreciate your work if they can’t understand it.” I think we spent more time discussing grammar and arguing over semicolons than we spent worrying about the actual physics. But it is some valuable advice: a well-written proposal has a better chance of being funded, and communications even became part of my job back when I was Cal Gillard’s translator!

A joke:

Little kid to famous magician: “I know 150 tricks! How many do you know?”

Magician: “six.”

The point is that, rather than trying to learn everything (e.g., how to use every piece of software out there), concentrate on a few and learn how to use them well. (At this point in the talk, I paused to show a couple tricks from Excel and PowerPoint, which I intend to write up as a separate paper sometime.)

Sherlock Holmes:

[Inspector Gregory:] “Is there any other point to which you would wish to draw my attention?”

“To the curious incident of the dog in the night-time.”

“The dog did nothing in the night-time.”

“That was the curious incident,” remarked Sherlock Holmes.

(from “The Adventure of Silver Blaze”, by A Conan Doyle)

A mad scientist often is only brought in as a last resort, after all the regular methods have been tried without success. Your job is to “Think Different”, and to listen for the dog that didn’t bark.

An excellent book on the topic of methods of thinking is the collection of recollections by Richard Feynman entitled “Surely you’re joking, Mr. Feynman!” In it, he gives a number of examples of how different people’s minds work in different ways. I, for example, see the solution – the world is made of rubber bands and flexible joints, and you just have to wiggle this and stretch that to see the answer (Fig. 20); whereas others see the world by equations – matrices and tensors, sort of like the scene at the end of the movie “The Matrix”. If you get the two of us working together on a problem, we’ll have a terrible time trying to understand one another – our minds are just too different! – but if we come up to the same answer, it probably is the right one!

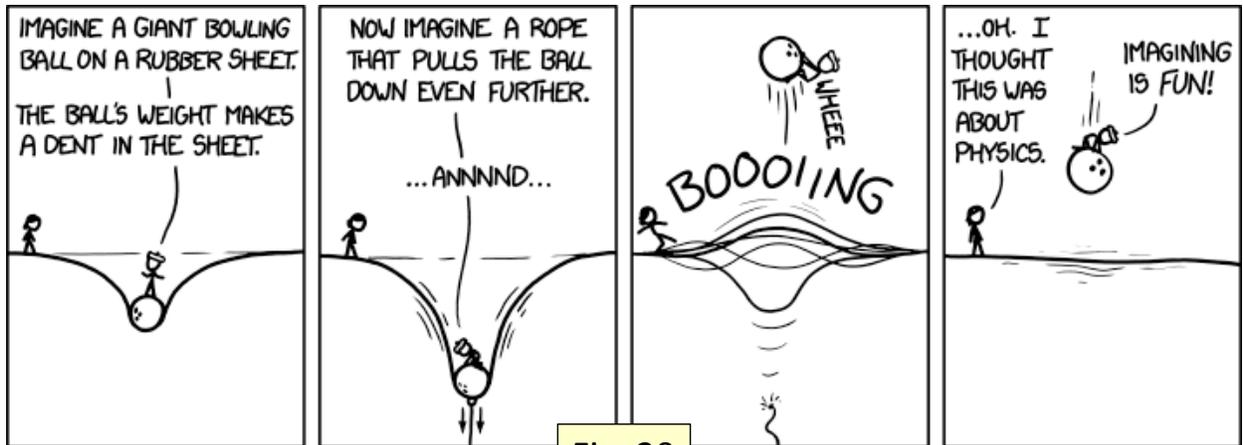


Fig. 20

Regarding visualization:

- It helps to make diagrams to visualize the situation – it is a way of confirming that you understand the problem and the parameters
- Provide sufficient detail to give context, but not so much that you're bogged down or it gets cluttered: use a level of detail that's appropriate for task at hand
- It helps to use basic colors (red, green, ...), not "sky blue", "periwinkle blue" and "baby blue": it's much easier to discuss over the telephone. (Also, avoid TLAs, and please include page numbers.)

You're basically making something like a subway map (Fig. 21).



Fig. 21

It's fascinating to see how different minds work.

One of my favorites is a puzzle I heard on NPR a few years back: Take the equation " $5 + 5 + 5 = 550$ ", add one line (and no messing with the equal sign!), and make it a true statement. Some folks can work on this for hours every day and finally arrive at the solution in a couple weeks, whereas others can see the answer within seconds.

Another example (see Fig. 22): there's a sheet of paper with words, some written in red, the rest in blue, and a clear glass (or plastic) rod. You are asked to look thru the rod, describe what you see, and explain it. (I used to use this as one of the tests when interviewing potential new hires. I wasn't interested in whether they got the right answer or not, but rather how they thought and how they responded to hints and comments.) The answer to this puzzle is in the Appendix. (The answer to the prior puzzle is too good to disclose!)

A common refrain:

“But that’s not the way we’ve always done it!” The reply is, “but how can you make it better (or fix the problems) if you can’t make any changes?”

I like relating a story I’d read about llamas:

Apparently, during WW II, the US Army tried to raise a herd of llamas in New Jersey, because...

Llama dung was required by the specifications in the processing of leather for airplane seats, and German subs had hampered the shipping of the stuff in from South America.

But why do the spec’s call for llama dung? Well, the US leather spec’s were copied from British leather spec’s; and the British leather spec’s were a century old (“that’s the way we’ve always done it!”), from the time of the British cavalry, for saddle leather: llama dung masked the odor of fresh leather and helped to calm the skittish horses so the draftees into the cavalry wouldn’t fall off their horses:

That’s why you need llamas to make airplane seats!

(I would send out my “llama tale” memo whenever I’d heard “But that’s not the way we’ve always done it!” once too often!)



More quotes from Sherlock Holmes:

“See the value of imagination!” (from “The Adventure of Silver Blaze”); and

“The world is full of obvious things which nobody by any chance ever observes.” (in “The Hound of the Baskervilles”)

With that in mind, I leave you, the reader, with a “homework assignment”: Observe the world!

- Explain to yourself the difference between “matte (or flat) gray”, “shiny gray”, “dull silver”, “bright silver”, “shiny silver”, and a mirror.
- Plot the “plane of the ecliptic” using the planets at night.
- Explain why your digital camera can photograph the orange of a pumpkin, but not the orange of a rainbow.
- Observe the shadow of the earth on the sky.
- Look for the “Green Flash” at sunset, and understand it.

(Solutions are given in the Appendix.)

In summary:

- imagine
- use your special tricks
- use common sense, and sanity-check the answers
- listen for the dog that doesn’t bark
- sniff out the llama dung
- have fun!

Step 2: Go Mad

Work at the same company for 30 years!

Thank you and good night!

Appendix:

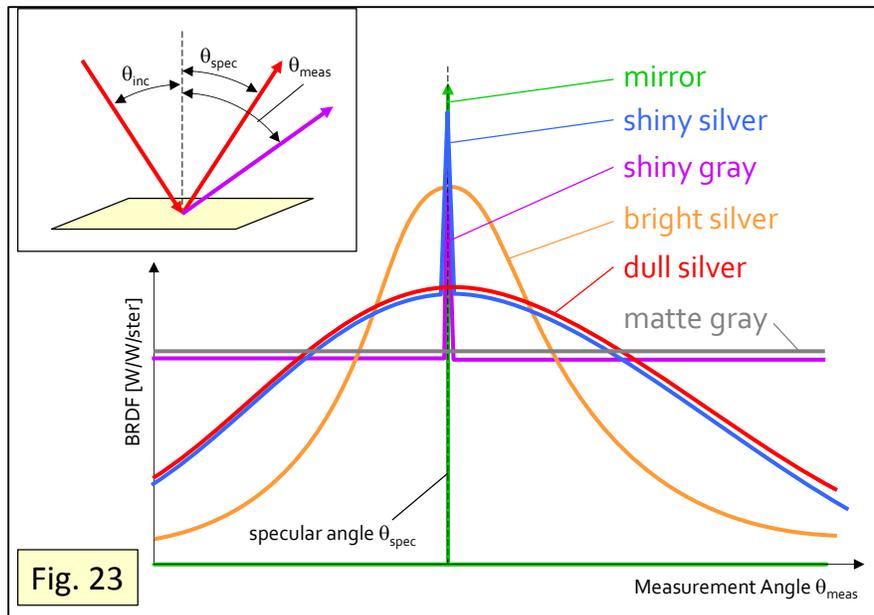
The words and glass rod puzzle

(Fig. 22): everything gets inverted – it’s just that the words in red used only letters with top-to-bottom symmetry. (I found this puzzle in the “Physics Museum” at the Univ. of Wisconsin. I used it on prospective new-hires: I didn’t



object too much if they tried to invoke Snell’s Law of Refraction, but I wouldn’t hire them if they insisted it must be Snell’s Law even after I’d pointed out the symmetry of the lettering.)

Silver and gray, etc.: they all have the same spectral (color) response and even the same overall reflectivity, but they have different “Bi-directional Reflectivity Distribution Functions” (BRDF) – see Fig. 23. Matte (or flat) gray reflects (scatters) the same amount



at all angles, a mirror reflects all the light in a single direction, and silver reflects preferentially in one direction.

The plane of the ecliptic: All the visible planets are in a plane. On some evenings, they are strewn in an arc across the night sky, and you can see where the plane of the ecliptic intersects the dome of the sky.

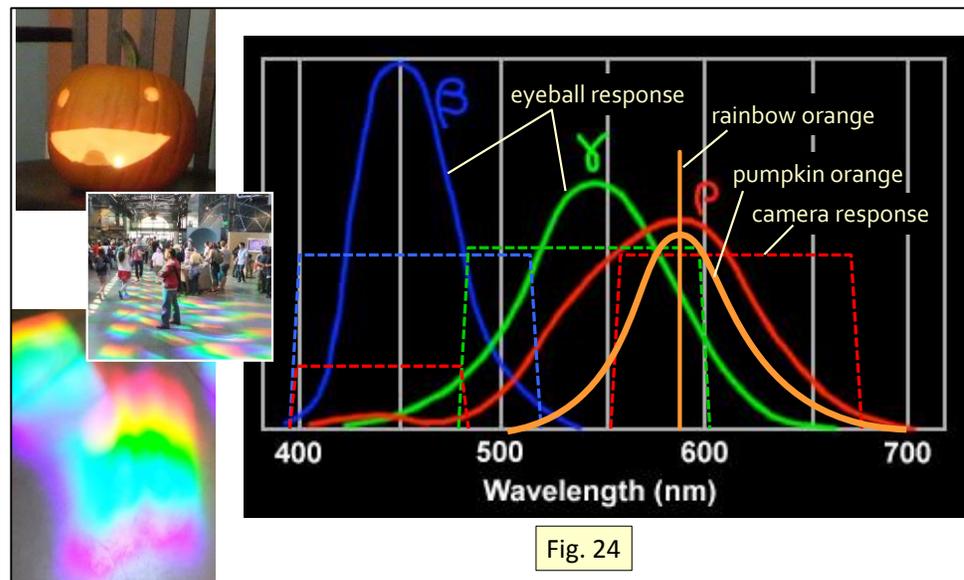
Orange pumpkins (Fig. 24):

The human eye can see color because the ρ , γ , and β cones in the eye respond differently to different wavelength light, sensing red, green, and blue variously across the spectrum. A digital camera also has red, green, and blue sensors, but they have a more flat spectral response: either sensing the color or not.

An orange pumpkin scatters light over wavelengths ranging mainly from red to yellow. The eye sees orange because the red cones fully sense the red, senses the orange pretty well, and modestly senses the yellow; the green cones sense the orange some and the yellow well, and the overall effect is “lots of red, some green” which gives “orange”. The digital camera sees the red, orange, and yellow as “all on”, and the green sensor sees only the orange and yellow as “all on”, and again the answer is “lots of red, some green” for orange.

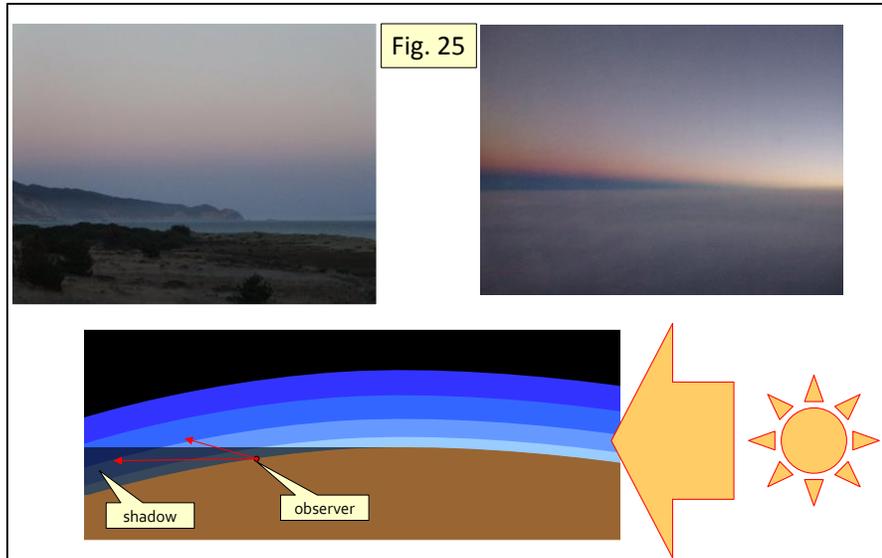
A rainbow is a pure spectrum (as are the patterns diffracted onto the floor at the Exploratorium in San Francisco). The orange in the rainbow is only one exact shade of orange, not a mixture of a range of colors. The eye senses that orange pretty well in red and somewhat in green, giving the “lots of red, some green” for

orange, but the digital camera sees the orange as red all-on, green all-on, which gives yellow. (As an aside: a digital camera can take a picture of a print of a rainbow, since then the camera pixels are responding to the dyes in the print rather than the narrow spectral bands of the actual rainbow.)



Earth's Shadow (Fig. 25):

This happens at sunset on a clear evening: the dark band of night rising in the east as the shadow creeps westward. It is especially apparent from an airplane.



Green Flash (Fig. 26):

This happens sometimes when the air is very layered, as happens on a “spare the air” day. You have to have an unobstructed view across a level surface (i.e., the ocean) towards the setting sun.

When there is a denser layer of air at the bottom, it refracts the light as if you’re looking into a swimming pool, whereas looking higher, you look out above that layer and see the sun’s truer position. As the sun sets, part of it is below the surface of the denser air and appears lower (or even already set) while the upper portion is still above the horizon. As there isn’t a sharp division between the layers, the line between acts

like a prism, splitting the sunlight into a spectrum. At the time of the flash, the red and yellow portion of the sun has already set. It’s not a blue flash because the blue light has already been scattered away by the atmosphere (that’s why the sky is blue and the sunset red), and so only the green light is left.



The flash only lasts a couple seconds and is not all that spectacular, but still it is an interesting phenomena.

Have fun!