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Mead's Analog Revolution

Of all our analog companies we have long been excited by the prospects of National Semiconductor and its spinout Foveon

When Bill Gates launched his new XP network-based operating system at a recent trade show, this king of the digital age did not begin by entering a password or clicking icons in a pop-up window. Instead he put his finger firmly on a glowing biometric touch pad that recognized Gates, loaded his personal settings, and gave him access to his personal files and digital kingdom. The company that supplied this open sesame is called **DigitalPersona**. But its innovation in pattern matching is *analog* and its technical leader, Vance Bjorn, represents a movement originating at Caltech in the mid-1980s to transform the world of analog interfaces to the digital world.

Dominating the PC touch pad market and breaking through the financial doldrums with the first successful Silicon Valley IPO of the last 12 months was **Synaptics** (SYNA), another primarily analog company, also with roots in this Caltech movement. **National Semiconductor** (NSM), meanwhile, is once again the analyst's darling among single chip system companies. But the bulk of the long run value in both National and Synaptics may be their shares in another company with a Caltech pedigree, **Foveon**, whose just-announced next generation silicon imager will finally overthrow photographic film. Over the next few years, Foveon may well become the dominant force in imagers in cameras of all kinds, still and full motion, a fast growing market of at least $20 billion today. Followed in the *GTR* since its founding in 1997, Foveon has fulfilled its promise with the single most powerful commercial technology I have seen since launching this newsletter in 1996.

But the story of this analog insurrection actually begins at least a decade earlier, in 1986, when the semiconductor industry was roaring back at last from a cataclysmic slump in which revenues dropped some 45 percent in a year. In a Caltech classroom, an eminent professor of engineering and applied science, like many in his trade, seemed to be flaunting his august connections in industry. Projecting the design of a massively parallel processor on the screen as a model for a revolution in computing, he said, "Now I've been up in Silicon Valley, talking to the guy who made this thing and…."

Why was this class laughing? Don't they believe in Carver Mead, the industry's first and most profound prophet of the very large scale integration (VLSI) of digital chips, who had performed the crucial researches on which Moore's law itself was founded? But the massively parallel design he was exhibiting on the screen to such friendly hilarity was not digital. It was analog. It was a schematic of the human brain.

In This Issue:

Mead's citation of the brain was not unusual in computer science. What was radical at the time was that rather than treating the digital computer as a possible model for an ultimately superior brain, he was offering the analog brain as a model of an incomparably more powerful computer. After twenty years as the industry's most authoritative proponent of the power of digital electronics, he was reversing direction and declaring the onset of a new era of analog. Prone to dour observations about the perceptual powers of digital computers compared to those of fruit flies, Mead maintained that what he termed "neuromorphic analog VLSI" offered the possibility of a radically more effective image processor. Later in the class, he presented the first example of such a machine, a silicon retina chip, modeled on the human eye, that could follow a rotating fan without aliasing (reversing direction like movie wheels) and could adapt to changing intensities of light. It was a significant first step toward creating a real-time imager on monolithic silicon. And among Mead's laughing students and auditors were several who would go on to form the vanguard of a broadband analog revival in the twenty-first century.

Foveon's new silicon imagers are the single most powerful new commercial technology I've encountered since launching the GTR

Yet, at the time, prevailing wisdom in the industry militated massively against doing a vision system in analog. Analog systems, everyone knew, could not scale to the huge densities of imager pixels. Requiring thousands of discrete devices, they loomed as too cumbersome to build and too wasteful of power.

Mead launches Synaptics

But there was Mead offering his device in plain bulk CMOS (complementary metal oxide semiconductor) silicon, slashing power by running the transistors at subthreshold voltages like the micro-power systems in digital watches. Rather than exotic discretes, the photoreceptors were created as part of the CMOS manufacturing process by turning a traditional CMOS bug into a feature. At the junction of every cell's two transistors—the complementary negative and positive devices—is a nasty potential bipolar transistor or "latch-up," a parasitic device that must be neutralized. Rather than neutralizing it, however, Mead listened to the technology and enhanced what the silicon wanted to provide.

Collecting light on its P/N junction, the latch-up transistor became an effective photoreceptor. With gain of over 1,000, the latch-up outperformed ordinary photodiodes that would have to be implemented off-chip. Integrating the photoreceptors onto the CMOS device, Mead showed the way to create analog systems that scaled like digital systems in accord with Moore's law. Within a few months, Mead launched a company called Synaptics to extend this technology to all the human senses, from hearing and imaging to touch. Joining him was Federico Faggin, the builder of **Intel**'s (INTC) first microprocessors and inventor of the self-aligned silicon gate that made them possible.

But there would be no giddy ascent for Synaptics or for Mead's new analog vision.

Analog? Digital?

For forty years, thanks in large part to Mead's own pioneering work in mega-scale digital systems and their design, the reduction of all information to digital numbers has seemed the essence of progress itself. As the chip burst beyond the backplanes of computers, thoroughly analog devices like cameras, radios, television sets, telephones, ovens, airplanes, and automobiles all began moving into the digital realm. Movie theaters will soon download their fare in multi-gigabyte files using technology from **Qualcomm** (QCOM) and **Williams** (WCG). Although most radios remain dominantly analog, the music that they broadcast originates on digital disks, where increasingly video also resides. New digital satellite radio systems are now emerging from **Sirius** (SIRI) and **XM Satellite Radio Holdings Inc.** (XMSR). And the digital camera continues its advance, dominating newspaper and magazine photography and making its way steadily into amateur cameras such as computer imagers. At the Consumer Electronics Show early this month in Las Vegas, **Hewlett Packard** (HP) introduced a tiny $599 digital camera with four million pixels. Experts spoke of CCDs (charge coupled devices) delivering as many as 16 million pixels—theoretically saturating the eye's ability to resolve detail just as the CD saturates the ear. With digital systems triumphant even in the realm of the senses, Mead's ideas for analog VLSI incurred solid resistance even from leading analog semiconductor companies, such as **Analog Devices** (ADI), **Texas Instruments** (TI), **Linear Technology** (LLTC), and **Maxim Integrated Products** (MXIM).

Appealing to the senses

At the outset, Synaptics targeted the three key human senses, touch, vision, and hearing. But for the first seven years the company made little progress in Mead's agenda of neuromorphic devices or large-scale analog neural networks. Only slowly did the silicon retina chip eke forward. In May 1991, after some 20 iterations of the device in Carver's lab at Caltech, it did make the cover of *Scientific American* in the form of the face of a cat registered by Mead's retinal camera. Inside, the story by Mead and his student, the late Mischa Mahowald, was confident: "The behavior of the artificial retina demonstrates the remarkable power of the analog computing paradigm embodied in neural circuits....A neuron is an analog device: its computations are based on smoothly varying ion currents rather than on bits representing discrete ones and zeros. Yet neural systems work with basic physics rather than trying constantly to work against it...."

In a sense, however, the cat on the cover—a blurred, almost unintelligible image in one color—was a downer, belying both the confident assertions inside and the grandiose claims of the Synaptics' business plan. Captured in only 2,500 pixels, the image seemed to pose no significant threat to the Moore's law juggernaut of digital electronics that was already propelling a thriving industry of machine vision for manufacturing applications. The key technology, which would also become the basis of digital photography, was charge coupled devices—a kind of silicon bucket brigade resembling a single stretched transistor with thousands of gates between source and drain that convert incident photons into electrons and pass them on in a serial array. With a single CCD chip holding millions of pixels, even then many company laboratories were experimenting with digital cameras that offered resolutions far higher than Mead's. Few were awed by his claim that he could scale his device to digital densities a hundredfold greater than the early rendition. Some 250 thousand monochrome pixels scarcely endangered **Eastman Kodak** (EK) or **Sony** (SNE).

The right feel

Synaptics faced financial failure until as a result of ingenious mixed signal inventions by Mead student Tim Allen, the company broke through in the mid-1990s first in the realm of touch, where Mead had done little work. So superior were the company's touch pads that they quickly took over the industry. Unlike rivals Logitech and Alps, Allen used a capacitive sensing pad rather than a resistive pad to identify the placement of the finger. A patented analog converter can locate the capacitance aroused by the finger on the pad to an accuracy of around 25 microns, or a quarter the width of a human hair. A totally solid-state solution in large-scale analog, the patented device palpably outperforms all other touch pads. Assembled in Thailand and then shipped to dominant PC manufacturers on Taiwan, Synaptics' superior pads came down in price to the point that rival Logitech exited the business. With a profitable run rate of $75 million, Synaptics is now fully engrossed in the touch pad business where it commands more than 60 percent market share (depending on definitions, as much as 80 percent). Possible new markets beckon in "toggle pads" and web appliances. Bursting through the tech market doldrums on January 28, Synaptics is the first vessel of Mead's analog vision.

Shortly after Synaptics' breakthrough in touch pads it became clear the company's very success would limit its focus to touch, shedding Mead's more ambitious sensory agenda. Mead eventually broke with Faggin and relinquished his role as chairman, though retaining his shares.

National Semiconductor partnership

Spun out of Synaptics was Mead's new company Foveon, 49 percent owned by National Semiconductor, a crucial partner contributing not only cash but analog chip fabs and all its intellectual property in imagers, as well as the man who created much of it, analog engineer Dick Merrill. Merrill is described by Mead as the most creative engineer he has met in all the combined disciplines of wafer fabrication, circuit design, device physics, and photography. Synaptics retained 15 percent of Foveon, likely to become that company's most valuable asset.

Bursting through the tech market doldrums on January 28, Synaptics is the first vessel of Mead's analog vision

Inspired by Mead's retina chip created at Caltech and work at **Apple** (AAPL) by Mead associate and Foveon cofounder Richard Lyon, Foveon is the most revolutionary vehicle of massively parallel analog VLSI. From the outset, Mead set the company up to master the intricacies of a camera system that could render authentic color. The key, Mead believed at the time, was to keep all the information in analog form as long as possible.

Dramatizing the challenge is the complete absence of color silicon imagers before Foveon. Digital cameras capture images on silicon and from those images produce color photographs. But the silicon photoreceptors operate in black and white. More precisely, they measure the intensity of the light striking them, not its wavelength. They are, if you will, indiscriminate photon counters.

Keep the information

In conventional digital photography progress from black and white to color is achieved not by gathering more information but by throwing information away. Over the photoreceptor for each pixel (roughly speaking the smallest component point in the image: think dots per inch in your ink jet printer) is a filter letting in only red, blue, or green light (the three colors captured by the rods and cones of the human eye). Thus, at each pixel the receptor measures only the intensity of one color, the immediately neighboring pixels capturing the others.

The camera thus starts by throwing away two-thirds of the information at every point in the image. It is never recovered. The final color image is produced by an elaborate digital guessing game, an algorithmic approximation whereby speedy but expensive digital signal processors project values for nearby red and green receptors onto the blue pixels, and so on. Because the algorithms function best by incorporating information from a range of nearby pixels, the guessing game for each can require a hundred arithmetic operations, one reason that at mega pixel levels the cameras waste time and power.

Ingenious as the guessing games are, the original decision to toss away so much information permanently impairs picture quality. Notoriously, certain color patterns trigger aliasing in the form of arbitrary rainbows, checks, and whorls where nature intended a blue shirt or a plaid jumper. As always in the digital realm, the preferred way over the rainbow is to do more with Moore:

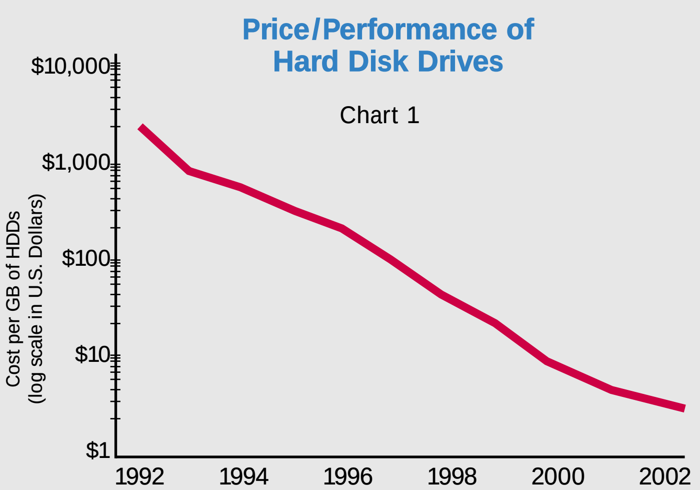
THE POINT OF LUNACY

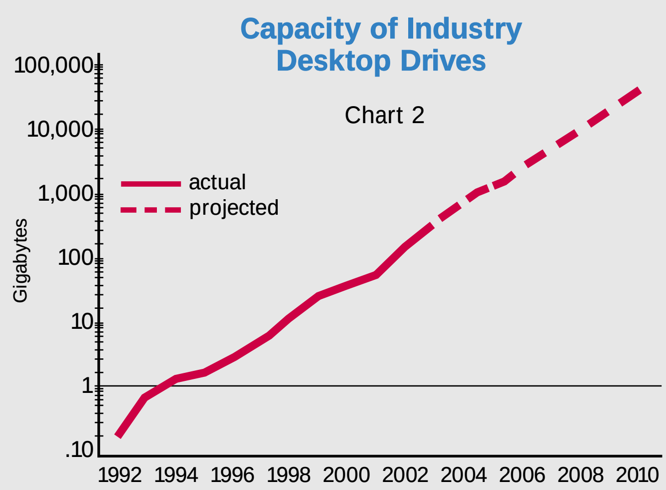
The annual doubling in price/performance that storage technology has enjoyed over the past decade (chart 1) has brought the major entertainment markets to the brink of massive disruption.

Naysayers believe that magnetic disk advance is rapidly approaching a roadblock—the superparamagnetic effect will cause price/performance rates to hit a wall—but optimists recognize that the industry has approached that same wall once every 10 years or so in the past 46 years and the industry has yet to crash and burn. With the recent discovery of pure nonmetallic magnets, working at room temperature, and technologies like holographic storage and mass MEMS-based storage on the horizon, we choose to continue to look past all apparent roadblocks.

By 2005, terabyte drives should be common in desktop computers and there's no reason why they could not be built into affordable stereo systems as well (chart 2). One terabyte stores the contents of over 25,000 CDs—far more than the combined active catalogs of all 5 major music labels plus all significant independent labels (chart 3). Perhaps 1 percent of the population will feel that their collections will not be truly complete until they include the complete *oeuvre* of out-of-print works, as well the full body of foreign music. One percent of the general population is also said to be schizophrenic. We can therefore think of one terabyte in the desktops as the "point of lunacy" in music storage—the point at which 99 percent of the media appetites of 99 percent of the people can be comfortably met in a consumer-class device.

The point of lunacy looms in television and film as well. Roughly 425 movies per year reach American theaters. By the end of the decade, the vast storage troves of TiVo-like set-top video recorders will conceivably be able to store MPEG-2 DVD quality video of every significant film shown in American theaters since World War II (chart 4). If you're more of a TV buff, delete the movies and use your TiVo-like box to record TV—all of it. Assuming the average channel broadcasts 100 unique hours of programming each week, within the decade set-top video recorders should be able to





as chip densities go up, add more pixels, with smaller receptors, and handle the burgeoning computational load with even faster digital signal processors (DSPs).

When digital systems exert themselves in the analog realm, however, the DSPs often hurtle at gigahertz pace blithely past crucial signposts from Mother Nature. Ultimately pixel size is limited not by Moore's law but by less tractable limits like the wavelengths of visible light—at roughly half a micron already dwarfing the smallest digital circuits—and the resolution of the human eye.

Mead was determined to avoid throwing away information. As Lyon explained, they wanted "no guessing at all." They wanted to "measure every color at every pixel." In the Foveon camera, every pixel would register real features of the image rather than digital simulations of it.

In the first generation Foveon camera that would mean tossing the filters and substituting a prism, splitting the red, green, and blue light and directing each to its own single chip imager. Then, instead of guessing, the signal processor would combine the actual red, green, and blue values for each pixel and produce the final image.

Foveon flies under the radar

The result was pictures of extraordinary quality, mocking even the best digital competitors and rivaling the Hasselblad studio cameras that establish the state of the art for film. It also meant a craft guild manufacturing process, producing handcrafted modules of glue and prisms, mirrors and multiple microchips all aligned with exquisite accuracy. At $50,000, the original sales price also marked Hasselblad as nearly their only competitor and professional studio photographers as their only market.

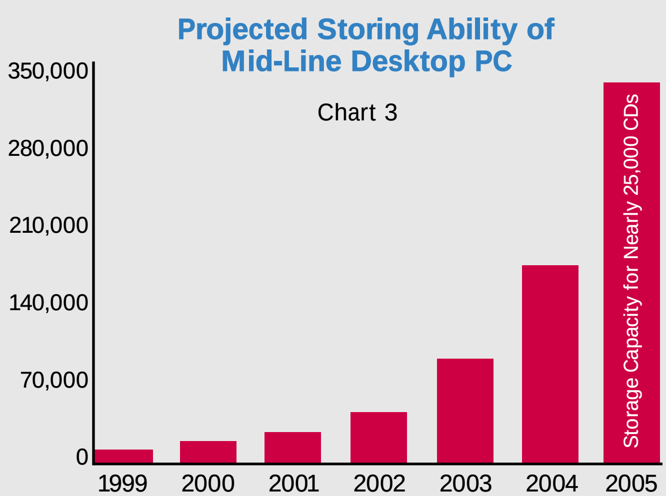
Fine with Mead. Let the competition scoff at the handcrafted prisms that would never enable a viable consumer store a full 3 weeks of output from over 100 different channels. Watch whatever you want, whenever you want, without any pre-planning. Fast forward buttons will make ads obsolete. Broadcasters and mass-marketeers beware.

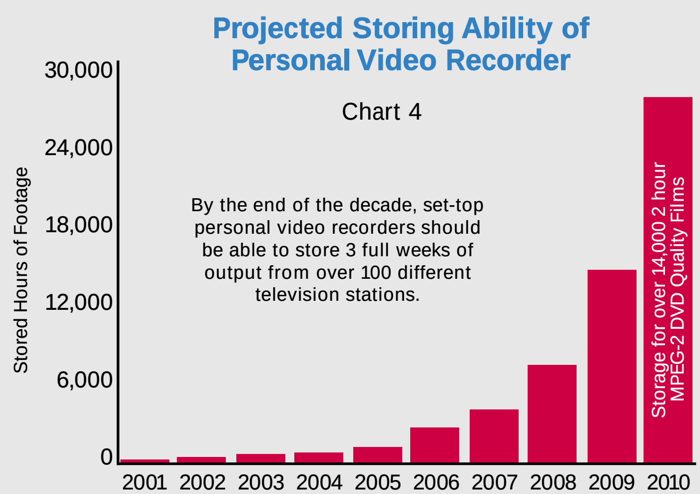
Relative prices of bandwidth and storage will determine the actual balance between data broadcast, downloading, and preloading. For music it will probably be most efficient to preload PCs, stereo components, and even cars with huge collections, kept current via satellite or wireline IP data broadcast. A continuous data broadcast of only 1 Mbps—an anemic trickle in tomorrow's bandwidth environment—could beam the contents of over 1,500 CDs to subscribers every week, far more than the combined weekly output of every significant music label in the world.

The cumbersome world of physical distribution, *a la carte* purchasing, and claustrophobically limited collections could give way to a readily accessible full body of music or movies (probably for a monthly fee in the case of music and a per-view fee in the case of movies). Even D-students in economics realize that when selection, convenience, and price performance increase by orders of magnitude, revenues and demand tend to explode. It happened with the rise of the VCR, producing the biggest economic bonanza in Hollywood history. Hollywood of course fought the VCR clear to the Supreme Court, twice. (Luckily for Hollywood, the VCR went 2-0.)

Music moguls likewise greeted the rise of digitally distributed music with horror and denial. But in the end, they and their comrades in film will reluctantly move with the technology. Any market vacuum that they leave will inevitably be filled with piracy. Broadcasters have more reasons to sweat. In all of these markets, storage is the easy part. Building the pricing models, payment systems, and rights protection schemes behind these services will be a contentious and challenging process, with large opportunities for creative entrepreneurs.

Rob Reid, Chairman of Listen.com
with Mary Collins Gorski





Data sources: IBM, Almaden Research Center, IDC

product. Let them conclude that Foveon was no threat. Flying in under the radar, the Foveon team would be free to pursue the real goal, a single-chip silicon color imager that would yield the best, cheapest, and easiest to use mass market cameras ever made, shedding not only film but virtually all the precision mechanics, including ultimately the shutter itself. Left would be only lenses and silicon, a true solid-state camera. But first the imager: Mead, Lyon, and Merrill had some ideas.

Through 1997, most of the ideas resided on Dick Lyon's desk, from which a few percolated to his brain. As part of the agreement with National and Synaptics, Foveon had inherited all the intellectual property on imaging held by both companies. Most of it, Lyon recounts, could be discarded. But Merrill had been a compulsive patenter at National ("Patents are a way to do something with an idea, without too much work. You dump it on the patent attorneys.") While at National, Merrill was trying to create out of CCDs a truly differential analog technology where only the deltas are measured and the noise drops out. Existing CCDs captured electrons (the negative energy) but threw away the holes (the positive energy). He patented a CCD that could keep both the electrons and the holes, and balance them off, registering only the changes. As Carver and Mischa had pointed out in the *Scientific American* article this is one of the fundamental advantages of analog systems, which "respond to differences in signal amplitude rather than to absolute signal levels, thus largely eliminating the need for precise calibration….Because only changes and differences convey information, constant change is a necessity for neural systems—rather than a source of difficulty, as it is for digital systems."

(The DigitalPersona fingerprint touch pad exploits this analog "change" phenomenon to differentiate between latent prints left on the touch pad and a live fingertip.)

Merrill's idea was based on the fact that different colors of light penetrate silicon to different depths. Bipolar P/N junctions buried at two depths on the chip would collect either the red light or the green, creating the differential analog levels. It didn't work: because one was red and one green the twain never met in a way that could enable differential analog. Instead, Merrill thought, this idea combining National's biCMOS process and transducer skills, might be useful someday as a color imager. Three buried P/N junctions could collect all three colors at a single pixel without filters, in effect tripling the "bandwidth" of the silicon plane. As the highest frequency and energy color, blue would be captured near the surface, only a half-micron down. The less energetic green would sink one and one-half microns before it agitated the silicon enough to be absorbed. The lowest energy photons—red—would penetrate down to three microns. One chip, every color at every pixel.

Foveon uses Moore's law of digital progress to rule the imaging world with an analog device

Alas, Merrill was convinced that a slight overlap of the blue, green and red levels in the silicon would make the system noisy, and unusable in a high precision application. True to the habits of a lifetime, he tossed the idea to the patent attorneys and then essentially forgot it.

It was Lyon, charged with mining the National IP for gold, who rediscovered it. He saw Merrill's objections, but working like Mead from biological premises, he observed that the eye is noisy in almost exactly the same way. Repeated six million times across the retina, the eye's three different cones identify the three colors with a small overlap. Lyon recommended that the engineers tweak the technology so that the overlap in the silicon correlated closely with the pattern in the eye, yielding an accurate rendition of colors as humans see them.

The magic of analog

Recalling that former Caltech scholar Tobi Delbruck, son of the Nobel Laureate, had come up with a similar idea, Mead was immediately impressed by Lyon's logic. The bipolar photo detectors repeated the original retina design, with not one but three buried junctions. If it proved manufacturable and effective, the single chip color image plane would repeat in analog the magic of the digital microcosm. It would be both better, cooler, cheaper, and lower power than its rivals, and it would scale, according to Lyon's calculations, to no fewer than 300 million pixels, far more than the eye could absorb. But whereas those excess pixels might be useless in a CCD device, the Foveon team saw that they would be the key to the solid-state camera. As chip processes improve, instead of making pixels exiguously smaller, more circuitry can be added to each, shifting currently mechanical functions like F-stop adjustment and auto focus to the silicon itself. The every-color-at-every-pixel-principle would facilitate the creation of pixel clusters, allowing Foveon to adjust dynamically the effective number and size of the pixels and thus their receptivity to light, the equivalent of allowing a photographer to change the ISO speed of his film between one shot and the next. At the optimum pixel count, the chip, requiring far fewer arithmetical operations than a standard digital device, could process images with virtually no delay, enabling a film quality video camera for motion pictures or a consumer to use a single camera for both home video and stills. With such bells and whistles increasingly providing differentiation in the camera market and expanding its margins, the Foveon imager would encompass on a single sliver of silicon essentially all the value of a modern camera except for the lens. In conventional digital cameras today, pixel proliferation is driven by marketing hype as companies try to persuade customers 16 million guesstimated dots is better than four. Transforming the pointless pixels into points of value, Foveon would use Moore's law of digital progress to rule the imaging world with an analog device.

Foveon's competitors become customers

But not as a camera company. Foveon is pursuing Clayton Christensen's innovation cycle, following an initial phase of integration (wherein quality results are so hard to come by that every aspect of a system must be integrated and optimized by the manufacturer) with a mature phase of modularity (wherein quality is so abundant that assemblers can use plug-and-play parts). By dropping prismatic handicraft for a single chip module, Foveon transforms its multi-billion dollar, market dominating, entrenched competitors into its multi-billion dollar, market dominating, entrenched customers. Sony is the world's leading digital image-maker. But Sony is the world's leading customer for digital image-makers and reportedly in negotiations with Foveon. So is virtually every other major camera maker, though no deals have been announced except for an alliance with **Sigma**, which will deliver the first Foveon enabled cameras to market later this year.

On the wall outside Mead's corner office at Foveon is a dramatic symbol of the amazing advances achieved by the company: a three-foot high image of the face of a cat. Rather than the blurry monochromatic sketch offered on that old *Scientific American* cover of ten years before, the new image offers a full-color vividness and verisimilitude never before achieved in photography. Some six square feet, the image resolves every hair, whisker, glint, and gleam of the feline fur and renders the eye of the cat with a lifelike glow that gives the viewer the distinct and disturbing feeling that a formidable animal is watching him. Yet the picture is of a kitten.

Enlarged to orders of magnitude its actual size, it shows not the slightest deterioration, distortion, or alias.

For the consumer today, the prime motive of digital photography is easy upload to the Web for storing and sharing. Ironically anemic digital images justify anemic compression technologies (JPEG) and anemic dial-up transmission pipes. The Foveon world demands better. It would be unsurprising, if Foveon's most important ally turned out to be an unusually large software company determined to extend its dominance of PC platforms to the Web.

Impinj to follow

On the surface, the year 2002 growls into view as a scavenger's feast—an epoch when much of the profit and property created during America's most cornucopian economic boom slips away into the maw of the most reactionary and obtuse parties: quasi-governmental bureaucracies such as **AT&T** (T) and **SBC Communications** (SBC), marginally competent foreign Internet companies such as **Cable and Wireless** (CWP), near nationalized corporations such as **France Telecom** (FTE), class action racketeers such as Milberg, Weiss, Bershad, Hynes and Lerach.

With my Telecosm list, my buy-and-fold portfolio, and the bold propositions of my book all in a shambles of deflation, I am inclined to be churlish. But following Mead's call to "listen to the technology," I still find myself rising in joy at its reveille, which is sounding with new urgency in the new year.

National Semiconductor retains 49 percent of Foveon and will also be its leading supplier and foundry, manufacturing Foveon's revolutionary devices in a leading edge fab in Portland, Maine. Following Synaptics and Foveon will be at least two other Mead companies, **Impinj**, a radical innovator in self-adaptive semiconductors, and **Applied Neurosciences**, a probable breakthrough venture in speech recognition. A kindred company, also associated with Mead, called **Sonic Innovations**, emerged in 1999 and is rapidly gaining ground in the global hearing aid business.

Soma and Narad unleash Internet traffic

This jumble of apparently unrelated companies all embody the singular new vision unleashed by Mead some 20 years ago in his classes at Caltech and brought to diverse fruition by an amazingly ingenious cohort of his students and associates. It signals the first hot flare of revival from the devastation of the last year.

New broadband companies **Narad Networks** and **Soma** are on the verge of transforming the local loop, both in cable and wireless, and will unleash an accelerating surge of Internet traffic, including Foveon's 20 megabyte to 40 megabyte per picture files. Meanwhile, the new backbone infrastructure that many of us haplessly helped to finance is still there. Like the railroads that bankrupted a previous generation of visionary entrepreneurs and built the foundations of an industrial nation, fiber optic webs, data-centers, and wireless systems installed over the last five years will enable and endow the next generation of entrepreneurial wealth.

Yes, deflation continues to grind through our list of leveraged creators of telecom infrastructure, such as **Globalstar** (GSTRF.OB), **360 Networks**, Exodus, and our services spearhead **Global Crossing**. Together with the anti-trust vandals who barred acquisition of **Sprint** (PCS) and MCI Internet facilities, deflation has drastically devalued Bernie Ebbers' colossus **WorldCom** (WCOM), with Internet leader UUNET and $28 billion of borrowed capital. The rising value of dollars in terms of gold, commodities, and other currencies still aggravates the debt of Telecosm companies, decimates their equity, and impoverishes their most visionary investors. Because of large borrowings backed by company shares, even Bernie himself is near bankruptcy. But the fiber optic networks, the data warehouses, and wireless access systems are mostly in place to enable a new ascent for the technologies on the frontiers of the Net.

Two more Mead companies will follow: Impinj and Applied Neurosciences

Central among these technologies since the launch of the *GTR* have been analog and mixed signal chips—transducers that link electronic systems to such real world forces as frequencies, amplitudes, temperatures, and pressures, crucially including light and sound. Texas Instruments, National Semiconductor, and Analog Devices were all early choices on our list. Comprising much of the rest of it, the all-optical network, from **Avanex** (AVNX) to **JDS Uniphase** (JDSU), is largely a manifestation of the advance of analog optics, which remove opto-electronic digital devices from the ganglia of global telecommunications systems. But of all our analog companies we have long been most excited by the prospects of National and its Promethean spinout Foveon. Today those prospects are fulfilled.

George Gilder and Richard Vigilante
February 14, 2002

TELECOSM TECHNOLOGIES

ASCENDANT TECHNOLOGY	COMPANY (SYMBOL)	REFERENCE DATE	/ PRICE	JAN '01: MONTH END	52 WEEK RANGE	MARKET CAP
FIBER OPTICS						
Optical Fiber, Photonic Components	Corning (GLW)	5/1/98	13.64	7.97	6.92 - 59.92	7.5B
Wave Division Multiplexing (WDM) Components	JDS Uniphase (JDSU)	6/27/97	3.63	7.00	5.12 - 61.00	9.3B
Adaptive Photonic Processors	Avanex (AVNX)	3/31/00	151.75	4.65	2.70 - 71.00	309.0M
All-Optical Cross-Connects, Test Equipment	Agilent (A)	4/28/00	88.63	30.35	18.00 - 56.30	14.1B
Tunable Sources and WDM Components	New Focus (NUFO)	11/30/00	20.31	3.45	2.10 - 62.88	261.9M
Crystal-Based WDM and Optical Switching	Chorum (private)	12/29/00	—	—	—	—
WDM Metro Systems	ONI (ONIS)	12/29/00	39.56	5.67	3.50 - 58.63	791.9M
WDM Systems, Raman	Corvis (CORV)	3/30/01	7.03	2.01	1.19 - 24.12	727.7M
Metro Semiconductor Optical Amplifiers	Genoa (private)	3/30/01	—	—	—	—
Optical Processors	Essex (ESEX.OB)	7/31/01	5.90	6.03	2.88 - 8.25	30.6M
LAST MILE						
Cable Modem Chipsets, Broadband ICs	Broadcom (BRCM)	4/17/98	6.00*	42.47	18.40 - 121.19	11.1B
S-CDMA Cable Modems	Terayon (TERN)	12/3/98	15.81	6.98	2.36 - 14.75	479.1M
Linear Power Amplifiers, Broadband Modems	Conexant (CNXT)	3/31/99	13.84	13.04	6.57 - 20.00	3.3B
Broadband Wireless Access, Network Software	Soma Networks (private)	2/28/01	—	—	—	—
Gigabit Ethernet Coaxial Cable Networks	Narad Networks (private)	11/30/01	—	—	—	—
WIRELESS						
Satellite Technology	Loral (LOR)	7/30/99	18.88	2.34	1.03 - 6.34	783.9M
Low Earth Orbit Satellite (LEOS) Wireless Transmission	Globalstar (GSTRF.OB)	8/29/96	11.88	0.14	0.10 - 0.30	15.5M
Code Division Multiple Access (CDMA) Chips, Phones	Qualcomm (QCOM)	7/19/96	4.75	44.13	38.31 - 89.38	33.9B
Nationwide CDMA Wireless Network	Sprint (PCS)	12/3/98	7.19 *	16.38	15.01 - 32.45	16.1B
CDMA Handsets and Broadband Innovation	Motorola (MOT)	2/29/00	56.83	13.31	10.50 - 23.65	29.6B
Wireless System Construction and Management	Wireless Facilities (WFII)	7/31/00	63.63	5.91	3.31 - 42.50	277.5M
GLOBAL NETWORK						
Metropolitan Fiber Optic Networks	Metromedia (MFNX)	9/30/99	12.25	0.41	0.25 - 19.94	339.5M
Global Submarine Fiber Optic Network	Global Crossing	10/30/98	—	—	—	—
Regional Broadband Fiber Optic Network	NEON (NOPT)	6/30/99	15.06	0.39	0.31 - 19.94	8.3M
National Lambda Circuit Sales	Broadwing (BRW)	6/29/01	24.45	7.99	7.44 - 28.50	1.7B
Internet Backbone and Broadband Wireless Access	WorldCom (WCOM)	8/29/97	19.95	10.05	8.70 - 23.06	29.7B
STOREWIDTH						
Java Programming Language, Internet Servers	Sun Microsystems (SUNW)	8/13/96	6.88	10.76	7.52 - 33.69	34.9B
Network Storage and Caching Solutions	Mirror Image (XLA)	1/31/00	29 .00	1.64	1.00 - 10.65	186.1M
Remote Storewidth Services	StorageNetworks (STOR)	5/31/00	27.00*	5.14	3.65 - 32.75	500.0M
Hardware-centric Networked Storage	BlueArc (private)	1/31/01	—	—	—	—
Virtual Private Networks, Encrypted Internet File Sharing	Mangosoft (MNGX.OB)	1/31/01	1.00	0.62	0.34 - 3.00	16.7M
Massively Parallel Global Storewidth Solutions	Scale Eight (private)	8/31/01	—	—	—	—
Secure Internet Business Exchanges	Equinix (EQIX)	11/30/01	1.65	2.29	0.33 - 7.00	183.3M
MICROCOSM						
Analog, Digital, and Mixed Signal Processors	Analog Devices (ADI)	7/31/97	11.19	43.80	29.00 - 64.00	16.0B
Silicon Germanium (SiGe) Based Photonic Devices	Applied Micro Circuits (AMCC)	7/31/98	5.67	10.17	6.01 - 80.94	3.0B
Programming Logic, SiGe, Single-Chip Systems	Atmel (ATML)	4/3/98	4.42	7.70	5.48 - 18.44	3.6B
Single-Chip ASIC Systems, CDMA Chip Sets	LSI Logic (LSI)	7/31/97	15.75	16.58	9.78 - 25.56	6.1B
Single-Chip Systems, Silicon Germanium (SiGe) Chips	National Semiconductor (NSM)	7/31/97	31.50	28.21	19.70 - 35.10	5.0B
Analog, Digital, and Mixed Signal Processors, Micromirrors	Texas Instruments (TXN)	11/7/96	5.94	31.21	20.10 - 45.98	54.1B
Field Programmable Gate Arrays (FPGAs)	Xilinx (XLNX)	10/25/96	8.22	43.35	19.52 - 59.25	14.5B
Seven Layer Network Processors	EZchip (LNOP)	8/31/00	16.75	7.70	2.70 - 19.25	56.1M
Network Chips and Lightwave MEMS	Cypress Semiconductor (CY)	9/29/00	41.56	21.76	13.72 - 29.25	2.6B
Field Programmable Gate Arrays (FPGAs)	Altera (ALTR)	1/31/01	30.25	25.12	14.66 - 33.60	9.7B

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TELECOSM TECHNOLOGIES

ASCENDANT TECHNOLOGY	COMPANY (SYMBOL)	REFERENCE DATE	/ PRICE	JAN '01: MONTH END	52 WEEK RANGE	MARKET CAP
FIBER OPTICS						
Optical Fiber, Photonic Components	Corning (GLW)	5/1/98	13.64	7.97	6.92 - 59.92	7.5B
Wave Division Multiplexing (WDM) Components	JDS Uniphase (JDSU)	6/27/97	3.63	7.00	5.12 - 61.00	9.3B
Adaptive Photonic Processors	Avanex (AVNX)	3/31/00	151.75	4.65	2.70 - 71.00	309.0M
All-Optical Cross-Connects, Test Equipment	Agilent (A)	4/28/00	88.63	30.35	18.00 - 56.30	14.1B
Tunable Sources and WDM Components	New Focus (NUFO)	11/30/00	20.31	3.45	2.10 - 62.88	261.9M
Crystal-Based WDM and Optical Switching	Chorum (private)	12/29/00	—	—	—	—
WDM Metro Systems	ONI (ONIS)	12/29/00	39.56	5.67	3.50 - 58.63	791.9M
WDM Systems, Raman	Corvis (CORV)	3/30/01	7.03	2.01	1.19 - 24.12	727.7M
Metro Semiconductor Optical Amplifiers	Genoa (private)	3/30/01	—	—	—	—
Optical Processors	Essex (ESEX.OB)	7/31/01	5.90	6.03	2.88 - 8.25	30.6M
LAST MILE						
Cable Modem Chipsets, Broadband ICs	Broadcom (BRCM)	4/17/98	6.00*	42.47	18.40 - 121.19	11.1B
S-CDMA Cable Modems	Terayon (TERN)	12/3/98	15.81	6.98	2.36 - 14.75	479.1M
Linear Power Amplifiers, Broadband Modems	Conexant (CNXT)	3/31/99	13.84	13.04	6.57 - 20.00	3.3B
Broadband Wireless Access, Network Software	Soma Networks (private)	2/28/01	—	—	—	—
Gigabit Ethernet Coaxial Cable Networks	Narad Networks (private)	11/30/01	—	—	—	—
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