A conversation with Mark S. Miller

by David Krieger

Part one: Creole physics and the credit theory of identity

Mark S. Miller is one of the system architects of the Xanadu project, the electronic hypertext system conceived by Ted Nelson as the future of publishing. Miller is also author, with K. Eric Drexler, of the Agorics papers (published in **The Ecology of Computation**, *B.A. Huberman, ed.; New York: Elsevier–North Holland, 1988) which first presented the idea of agoric open systems – computer operating systems in which system resources such as memory and processing cycles are traded by programs and processes on an internal open market. I spoke with Mark in Palo Alto, California in September 1992, and began by asking him about what he calls "creole physics":*

In several different areas, what we find is that we seem to have, in the case of language, a particular grammar wired into our brains as kind of our initial grammar. When I say wired into our brains, it's not necessarily the case that you can look at the genotype and see the grammar directly encoded in there, but in the sense of Dawkins' extended phenotype[1], that a particular grammar seems to be the phenotype of our genotype. The reason we have confidence in this, is that there is this process that there are at least three clear instances of, in which what linguists call a creole grammar arose. This process is one in which the first generation of children who grow up speaking creole are in a linguistic environment which does not constrain their grammar and to a large degree doesn't teach them grammar.

You may want to go into the definitions of a pidgin and a creole.

When a bunch of people speaking a bunch of different languages are somehow thrust together by weird historical circumstances — especially when they're trying to engage in trade with each other, which is a reason for different language speakers to constantly be in contact with each other — the language that they end up speaking is termed by linguists a pidgin language. The characteristics of a pidgin language are that the vocabulary is a compromise between the vocabularies of the different languages that fed into the pidgin, but the grammar is not. To a significant extent, to a good first approximation, a pidgin language has no grammar. It really doesn't do very much positional encoding, and you simply communicate by trying to put all of the content into the vocabulary words. However, if you listen to a given pidgin speaker, you can tell what his original language was, because he'll be using the grammatical constructs of his native language, he just will no longer be encoding meaning in that.

Right.

The children of pidgin speakers are in the closest approximation to sort of the "ideal fantasy linguistic experiment."

The "state of grace."

Yeah, the "state of grace fantasy linguistic experiment." The sort of thing that you would clearly love to be able to do as a linguist would be to somehow get a group of human infants who've never heard a human language and put them together on an island tended by robots or deaf-mutes or somebody — specifically, deaf-mutes who didn't know sign language, a completely non-linguistic environment — and let them just, in interacting with each other, spontaneously start speaking some kind of language, and just see what the structure of that is. Also, you'd want to do that experiment repeatedly with groups of children over and over again so you get some statistical distribution. Now, there's all sorts of reasons why, logistically and ethically, and developmentally probably, this is not a possible experiment.

However, the children of the pidgin speakers are raised in what is probably the closest to this experiment you can ever get to, which is: They're raised in an environment in which their parents don't consider any grammatical construct to be correct or incorrect, so they're free to use whatever grammatical constructs they use, and it doesn't get corrected. Every time that there's been a clear case of this historical circumstance, the creole language that results — the language that the children of the pidgin-speakers speak — has the same grammar. And the most recent case, which is Hawaiian pidgin and Hawaiian creole[2] — they did this research while not only the original Hawaiian creole speakers were still alive but while the original Hawaiian pidgin speakers were still alive.

They were able to determine that the grammatical constructs of the Hawaiian creole speakers were not only the same constructs as in other historical creole circumstances, but they were grammatical constructs that were found in *none* of the languages that were inputs to Hawaiian pidgin. It couldn't have been transmitted culturally, so you have definite non-transmission of a grammar that arises spontaneously every time this thing happens.

In addition, once they had this hypothesis in hand with this one verification, they said, "Okay, if this hypothesis is true, then what we should find when studying children growing up learning to speak English, is that where English and creole agree, the children should basically get the English constructs immediately, and where English and creole disagree, the children should start out speaking the creole construct, and have to have it corrected into the English construct. And they found exactly that.

The one particular case that I remember from the article — although the article has a lot of examples of this — is "double negative meaning emphasized negative." That's a creole construct. From a logical first-principle point of view, it's clearly more complicated than a "double negative meaning a negated negative," i.e. —

A positive.

A positive, or at least the absence of a negative. So double negatives are something that children end up starting to use and they have to get it corrected into not using double negatives. As we all know in English-language culture at least it's only partially corrected.

In any case, that's one example of having this native inborn large structure that's an approximation of the culturally-evolved structures that we're used to, and it's the thing that starts the boot-strapping process off, where we come at life with this biologically-constructed —

Set of pre-conceptions, actually.
Yeah, and then we get it corrected into a more culturally-evolved and hopefully a more sophisticated one.

Other examples are "naive physics." With naive physics, what they've done is they've interviewed people, given them little tests, and said, "Intuitively, what do you think would happen if you took a ball that was going around a circular wall, and when it got to the end of the circular wall, which direction would it drop?" The correct Newtonian answer should be obvious —

Tangent, basically. It continues going in a straight line.
Right. But an amazing number of people will think that it either continues circular or will spiral outward. With "naive physics," what you find is that, even in physics students who have gone through first- and second-year Newtonian physics, naive physics is fairly unperturbed. If you ask the questions in the right way, where you still get at what their intuitions are, as opposed to making them feel like they're on a physics test and keying into their training, what you find is, their intuitions have been largely untouched by the training, and they still have the same intuitions as people who have not learned physics, and the intuitions actually resemble Aristotelian physics to a large degree. The significance is, the Greeks not being experimentalists, Aristotle cataloged not physics, but human psychology about physics, and I think it's interesting to think of that as a theory.

Popper is very clear on the analogy between biological evolution and theories, and in fact over here we have a very nice mixed case of a biological evolution of a theory of physics, which was "good enough". Biology stops, basically, when it gets to a "good enough" solution, especially when it's an adequate-enough solution that any creature is able to carry forward from there using cultural evolution.

To an extent, biologically-derived theories are falsified through species or individual selection, in that, if your model of physics is "wrong enough" to expect the ball to do something completely — not even in line with "naive physics," for instance to move out of the plane of its motion, something that wrong — animals with that model will presumably be selected out, if it's wrong enough to make a survival difference.
This is a complete aside, but I think it's interesting, and I also think it's original: A lot of people look at naive physics, and think just on the kind of stuff we've already said. "It's good enough, and there are things about it that are wrong, but that's okay; culturally, we can correct." I think that it's actually better adapted as a physical theory in many ways, than Newtonian physics is, to the world that our ancestors were in. Here's specifically the thing that I mean by that: Everybody assumes that naive physics is primarily a physics of inanimate objects. However, I think that a lot of the ways in which it's wrong are actually by virtue of being more adapted to being a physics of animals.

There's a certain animism in expecting the ball to continue on a curved path as if it has an intention.
Exactly. There's also a certain animism in thinking that "It's been constrained, and now it's free, so now it's going to overcompensate." Either one of those are intuitions that are good at trying to predict the behavior of intentional creatures.

Popper is very clear on the analogy between biological evolution and theories, and in fact over here we have a very nice mixed case of a biological evolution of a theory of physics, which was "good enough."

I was going to say, you've "adopted the intentional stance" toward your particle or projectile.
Exactly. Most of what we needed to interact with and predict successfully were animate objects, many of whom were trying to evade us, so it would be appropriate to devote more of our resources to trying to predict them than to predict these nice cooperative, or at least not hostile, inanimate objects.

So to a certain extent, Aristotelian physics is still with us, and will continue to be with us until we start monkeying around with our genes.
By the way, there's one very interesting example of this. This is the thing that really made me add the animism to this. The way I came by this animism thing is after reading a fascinating paper about some computer animation work.[3] An interesting peculiarity which has long been known to animators is that, when you draw an animation of a bouncing ball, there are certain things that you can do that are violations of Newtonian physics — rather gross violations — that actually are known to make the animation sequence look more realistic. If you do it realistically, it actually looks less realistic than if you introduce these distortions.
Now, what the distortions are, is that a ball, before it hits, elongates in the direction of motion, and then it hits and it flattens out. Also, there's another similar thing — let's just deal with that one, that's sufficient.

In this computer animation work, it was work in animating animals. In which what they did, well, they actually used a Luxo lamp as a "virtual animal", a Luxo lamp being this nice simple structure that's easy to animate, that you already have the database for —

I've seen the cartoon; the one that I saw was called "Luxo, Jr."
I'm not sure if "Luxo, Jr." actually used this technique; I think instead it's because the database from "Luxo, Jr." was already available, that they decided to do this work with the Luxo lamp.

What they did is, they wanted to make the Luxo lamp move around the way you would imagine an animal would move around. They did that by setting up an energy minimization problem. They sort of said, "Okay, the struts of the Luxo lamp are a skeleton, the joints are joints, and we will just, in our calculation, come up with a muscular model for bending the joint." Specifically, a model of the relationship of force and torque versus energy expenditure. Then what they did is they said, they basically had the following problem: the Luxo lamp is stationary on the ground over here, there is some kind of barrier between it and the goal, and it needs to get from where it is to the goal, and end up stationary at the goal, not just at the goal but stationary at the goal, and it needs to do that with a minimum expense of muscular energy. Fortunately, problems like this are sufficiently monotonic that you can solve them with straight hill-climbing.

What they ended up with was a motion in which the Luxo lamp first *crouched down*, then extended in a leap, then contracted back together, and moved its base forward. After it was over the barrier, it elongated itself —

In preparation for landing.
In preparation for landing, and then did a soft landing and came to a stationary position. So, they observed in their paper, that this has reproduced in a principled way, the trick that animators always knew about, and what I think they didn't go on

to explicitly say, although they may have, but I'll certainly go on to explicitly say, is that even at those very low levels of our visual apparatus, we have this very intentional physics, in terms of our expectations and perceptions of motion, and that's why motion of the inanimate object which is distorted towards animate motion, actually looks more realistic.

So, back from the digression: Kahneman, Slovic, and Tvursky[4] , and also a book called *Human Inference* by Nisbett and Ross[5], catalog a whole bunch of ways in which human statistical inference is very badly flawed, but distorted in systematic ways, and there are many many problems that result from the distortion, but, to some extent, society — we are all escaping from those problems by virtue of the modern understanding of statistics.

Another topic I wanted to ask you about was your views on the question of identity, especially as it applies to cases like uploading and duplication.

It seems to me that most everybody comes at the identity question with the presumption that there is some hard notion of identity that's real, and that all we need to do is find a definition that's good enough that corresponds to the notion of identity that we have this compelling sense we must be able to find. I think that the whole sense that there must be some real notion of identity that's preserved over time and over change of state, and change of information, et cetera, and it's really a discrete sense of identity, that you can still use to reason about a world with uploading, with backup copies, and with, especially, I think the most challenging one, having a communication medium between people such that the bandwidth between brains is the same as the bandwidth within a brain, in which case, the discreteness of the individual — I think that's probably the one most challenging to the notion of discrete individuals.

The reason why we have this compelling sense that there must be a definition of identity is what I'll call "creole epistemology." I think that so far historically we haven't lived with uploading and with backup copies and with high-bandwidth communication between brains —

So our intuition hasn't been selected for accurate portrayal of that sort of world, and what we intuitively guess about those is probably not accurate and probably not the most evolutionarily-stable strategy of epistemology.

So this set me on the following search. I think it's also the case that trying to dispense with the notion of identity altogether is not the right way out.

Though it's very popular.

There's all sorts of abstractions that we use to understand complex systems, and denying any reality to some kind of notion of identity out of a reductionist sense that identities aren't real, is to fall into the reductionist fallacy, to use a metaphor of Dean[Tribble]'s, of "denying that the window on my Macintosh is real because it's only built out of pixels." So what I'm looking for is some notion of identity which has the right kind of fluidity to it and still the right kind of sense of coherence and continuity over time and over change, such that, by using that notion of identity, it can be an aid to intuition about post-Singularity life, not a hindrance to it. What I came up with is the notion that we already have the right kind of intuition about the identity of civilizations, the identity of cultures, the identity of natural languages.

So what I'm looking for is some notion of identity which has the right kind of fluidity to it and still the right kind of sense of coherence and continuity over time and over change, such that, by using that notion of identity, it can be an aid to intuition about post-Singularity life, not a hindrance to it.

Let's concentrate on civilizations. One of the key insights that led me down this path was something that I got from my pediatrician, Dr. Einhorn. When I was a kid, I was reading some stuff about the Greeks, and I was really fascinated by the Greeks, and I was home sick and my pediatrician was seeing me, and I got into a conversation with him about Greek civilization; and he also thought the Greek civilization was real neat, and then I mentioned that, "It's really a shame the Greek civilization died." And he said, "They haven't died; we're it." And at first I just had no idea what he meant by that, and then he explained that so much of what our civilization is and where it comes from, is based on the ideas of the Greek civilization, and so many of the values that we have, evolved out of the values of the Greek civilization, that, in a lot of ways, it really makes sense to think of the Greek civilization, for some descriptive purposes, as being who we are.

The thing that's very nice about what people understand about the identity of civilizations is that people are already used to the fact that civilizations aren't really discrete, they blend and flow into each other, there's multiple influences from multiple paths, and drawing a boundary in space-time around a bunch of people and cultural practices and saying "This is Civilization X" is clearly something that we do as observers, and that we have the choice of several different boundaries. We can't argue that any one set of boundaries is correct. So, in that sense, no set of boundaries is objective, but neither is it the case that all boundaries are equally good; it's not the case that "Anything goes," and "It's all just subjective" in the sense of "Whatever the hell, anything goes, it's all just in the eye of the beholder anyway" and "Why should my boundaries be any less good than your boundaries?"

Another thing about this is that, when we really think about whether or not we should say that "The Greek civilization isn't dead, we're it," whether there's that kind of continuity, largely we're not thinking so much in terms of "pattern identity," to use the phrase from *Engines of Creation*[6], because our civilization currently is very, very different from Greek civilization, and we're also not using the notion that's very common of "continuity of consciousness," because people generally don't speak of civilizations as being conscious, and besides that, the Greek civilization was suspended in cryonic suspension until its literature was rediscovered.

The question is, what's the criterion we use when we say, "We are the successor to the Greek in such a way that this vague descriptive notion of identity is preserved." That was resolved for me by hearing about Fukuyama's book *The End of History and the Last Man*[7]? So, leveraging off the description that I've heard of that book, I realized that the key issue is credit — credit, and respect, and admiration — Which previous state do we feel good about giving the credit for having been our younger selves?

I think this lets us get past what would otherwise be the terrible paradox of seeking long life in a post-Singularity world, which is: Should you seek to not grow? If you're coming at things from a pattern identity point of view, then to the degree that you expand and learn and grow, you also die — your previous self has died. So, from the point of view of someone who constructs his goal structure by starting with "I choose life, I want to live," the pattern identity notion would lead you to seek to constrain your future choices to prevent your growth into something that is so far beyond your current self that you're no longer like your current self.

I think that the goal, if you reconstruct the goal of wanting to live in terms of this notion of continuity of identity through credit, a particular kind of credit that's really neither of the ones that Fukuyama mentioned, that's the one that I know I most crave in my intellectual pursuits, is the respect of people I admire. The greater my admiration for those people, the greater my satisfaction in getting any respect from them. They might not even respect me as a peer, but if they respect me at all, the higher my estimate of them, the more that respect for me makes a difference to me.

What I seek to become is a creature that is vastly, vastly greater than my current self, something that is magnificently greater than my current self; and I translate my desire to live into my desire to have that future magnificent self look back on my current puny self with some credit–

And recognize the debt that it owes you.

Right. Yeah, "I'm thankful to that guy for having had the seeds to become me." Just like I look back on my four-year-old self and realize, "Oh, yeah, that guy, I can just kind of give him credit for having had what it took to grow into my current self." Let me make a meta-point, by the way. Both myself and the Xanadu project as a whole are very, very careful about credit and references which is in some sense why we're in fact doing this hypertext system where you can make all these links to source material —

Yes, that's been noted several times before about the whole XanAMIX crowd, and one of the reasons that attracted me to come up here and join in, is the meticulous pinpointing of giving credit where credit is due, and the willingness to spread around credit among sources. That ties in closely with what you said about credit identity —

To the extent that we're citing our formal selves, our more primitive selves, for the germs of what we become.

About these boundaries being between subjective and objective — Don Lavoie referred me to a book[8], the basic point of which is that philosophy has been stuck in this false dichotomy: that things are either objectively true, or they're in an anything-goes state. In fact, most everything is in this third state.

Don comes at it from a hermeneutical point of view, and you can think of these issues as very literary ones, where certain choices of descriptive boundaries "make for a better story" about history than others. You can't objectively say that one novel is better than another, but we all know that novels are not all equal; that novels really are better than each other, but there's no objective way to determine in a disagreement which is which. In some sense it comes down to a matter of taste, but in some sense it doesn't really, because there really is a content to what we're arguing here.

A lot of matters of taste rely on being consistent with a set of cultural assumptions, in that, although there's no direct reason for saying that one novel is better than another, there are cultural qualities, based on which, valuing what we consider to be the inferior novel would be inconsistent with certain other assumptions in our culture.

But I believe that even cross-culturally, and even, hypothetically, across species, you'll find that there's enough agreement about some of the extreme cases, especially the extremely bad cases, that there's clearly something going on here that's not just arbitrary and anything goes, but it's also not objectifiable. I don't come at this from a hermeneutical point of view, but from an evolutionary-epistemological point of view. That's simply because I have not gotten into the hermeneutical literature yet. I believe, from what I understand of hermeneutics through Don Lavoie, that there's actually a lot more agreement between the two philosophies than the practitioners of either are inclined to recognize or acknowledge, which is unfortunate.

From this evolutionary-epistemological point of view, all of our knowledge arises out of a process of variation and selection. You can think of the variation component of the evolution of knowledge as being the subjective component, and the selection component (where the selection is by external criteria — there's also subjective selection, but we'll leave that aside), the selection is by virtue of getting mugged by reality. It's through the selection that we get the objective component, but therefore all of our actual knowledge embodies a mixture of the two where it's impossible to separate the mixture. We can understand the process, but we can't tell, for an individual piece of knowledge, how much of its content came from the variation process and how much came from the selection process.

You said a little bit earlier about continuity of consciousness as a criterion for identity, and you said that Greek civilization was "cryonically suspended" in the form of literature until it was revived. Does consciousness exist? Is consciousness necessary as an assumption, as a hypothesis, or can your personal epistemology get along fine without consciousness?

I think that, similar to identity, there's a lot of strong intuitions we have about consciousness that are a result of creole epistemology. As well as a result of things that culturally evolved between Freud and computers. There was a lot of evolution of the notion of what consciousness is between those two events, and essentially our folk psychology — which is a wonderful phrase of Dennett's — is still largely a result of that pre-computer evolution.

What I seek to become is a creature that is vastly, vastly greater than my current self, something that is magnificently greater than my current self; and I desire to translate my desire to live into my desire to have that magnificent future self look back on my current puny self with some credit.

There's many parts of what we mean by consciousness. The idea of there being a "real you" at a point inside you that experiences things in a serial order and knows what it believes — understand, I have not read the book — but from what I understand, Dennett does a very good job of trashing that, and I think it well deserves to be trashed: homunculus theory?

That's what Dennett calls it, the homunculus, the "little man in the control room" —

By the way, let me strongly recommend to everyone the segment of Woody Allen's movie "Everything You Always Wanted To Know About Sex, But Were Afraid To Ask" with Tony Randall in the control room of the guy who's having sex, and Woody Allen as a sperm who's agonizing about "What if he's not even having sex? Maybe I'll end up on the ceiling!" And the thing that's wonderful about that is it's a very strange and wonderful mixture of homunculus theories, and society-of-mind theories; it's kind of got a lot of mixture of both. It's actually very sophisticated. I really recommend going back and watching that after having read *Society of Mind*.[9]

Okay.

So, our notion of consciousness that has much truth to it, is the notion of consciousness being reflective — that it really is quite a trick to be able to have been doing something without articulating to yourself what it was you were doing, and then to "hop back" and say, "Oh, so I was doing that" and then you're articulating, you now have a thought you can think about. And this whole ability, not just to introspect, but one of the things we notice about articulate knowledge versus inarticulate knowledge is that inarticulate knowledge is learned gradually with training. Articulate knowledge, through, I'll say, through the mechanism of consciousness — and what I mean there is purposefully vague — is able to learn many things on one hearing, because it's manipulating a very different kind of learning process. A lot of the trick of the brain is the gluing together of those two very different kinds of learning, and, in particular, the way in which they each bootstrap the other.

Another aspect of consciousness that is valid is that part of the trick of consciousness is that your articulate construction of the world has as part of its articulate construction a symbol in there if you will — a designator, a node — that represents this creature itself. So this notion of consciousness is intimately tied in with the notion that we have of identity, which is: our creole notion of identity is the thing that's there in that slot —

Experiencing the consciousness.

In the conscious articulation of how the world works and what's going on there, there's this idea structure of the identity of this personal self that's a creole self — a creole identity of the self as well as a creole identity for consciousness — but that's the thing that the rest of the conscious structure uses in thinking about its place in reality.

So I think that all of those are valid pieces and part of the pattern, but I think that not only is a lot of our other stuff about consciousness, like the homunculus stuff, wrong; but a lot of the stuff that's right is much less important than people verbally think it is — that, in some sense, we're much less conscious than we think we are, and the reason is that the thoughts that we're aware of, are the ones that we're aware of.

Can you give an example of an instance in which people are less conscious than they think they are?

Okay. People generally think that they have a lot of introspective access to how they think. However, for relatively simple computational tasks — the kinds of things that people are conscious of what they do, of how they do it when they do it — are generally much simpler computational tasks than the things that people completely take for granted and do "without thinking." The fact that so many of those are of such incredibly greater sophistication than the things that we do "with thinking" means that the fact that we think that it's in our "thinking" process that's where the sophistication lies, is probably wrong.

One particular example that I really love is "Hansel and Gretel." In the book *Distributed Artificial Intelligence*, edited by Bond and Gasser[10], one of the papers has this diagramming notation which they're exploring so they can diagram not only "Actor X believes A," but they can diagram what people believe about other people's beliefs. "At this point in the story, this guy believed that *that* guy believed that this person was going to do *that*, whereas this person himself believed that *this* guy believed that he himself was going to do something else."

Right.

So they've got a good diagramming notation for laying out these kinds of nested belief structures. They explain this by diagramming the beginning of the Hansel and Gretel story — the part of the story that is *before* it gets interesting — the part that you just read to a kid and assume that he gets it "without really thinking about it." It's not considered to be a tough comprehension for very small children, but you end up with this massive structure to explain it. I think I'm good enough at evaluating notations and formalisms to look at it and say, the massive structure is not the result of a bad formalism. The formalism is good; the formalism does not create any combinatorial explosions here. The massive structure is the result of the fact that human beings are wired for this incredible ability to do nested modeling of belief structures — very nested modeling, three and four levels deep without straining.

It could also be considered empathic in the sense of putting yourself into someone else's position and modeling their beliefs by adopting their viewpoint.

I think that one of the reasons that people always seem conscious to us, and no AI system has seemed conscious to us yet, is that when I form a model of you "without thinking about it," part of my model is my model of your model of me, and my model of your model of my model of you. It's certainly the case that no AI system has enough knowledge of our social conventions and of other human beings that, when we're interacting with an AI system, the models that we construct that have explanatory power to us about how it's going to behave, don't include that kind of deep nesting because it doesn't have enough ability to accurately understand my model of it, or its modeling of my model of it, to have influence in what my model of it is. There's a lack of the kind of deep nesting that we normally do "without thinking about it" with human beings, and I think it's what that kind of deep nesting provokes, that is what we have attached the label *consciousness* to. That's why, no matter how reflective a computer system is, it never seems conscious to us.

In Part Two of this interview, Mark and I discuss the five kinds of libertarianism, the Reverse Polish Moon Treaty, "nanarchy," and the role of gossip in a free society.

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Nanocomputers

21st Century hypercomputing

J. Storrs Hall

If the price and performance figures for transportation technology had followed the same curves as those for computers for the past 50 years, you'd be able to buy a top-of-the-line luxury car for $10. What's more, its mileage would be such as to allow you to drive around the world on one gallon of gas. That would only take about half an hour since top speed would be in the neighborhood of 50,000 mph (twice Earth's escape velocity).

Oh, yes, and it would seat 5000 people.

Comparisons like this serve to point out just how radically computers have improved in cost, power consumption, speed, and memory capacity over the past half century. Is it possible that we could see as much improvement again, and in less than another half century? The answer appears to be yes.

At one time, people measured the technological sophistication of computers in "generations". There were vacuum tubes, discrete transistors, IC's, and finally large scale integration. However, since the mid-70's, the entire processing unit has increasingly come to be put on a single chip and called a "microprocessor." After these future advances have happened, today's microprocessors will look the way ENIAC does to us now. The then-extant computers need a different name; we'll refer to them as nanocomputers. "Micro" does exemplify at least the device size (on the order of a micron) and instruction speed (on the order of a microsecond) of the microprocessor. In at least one design, which we'll examine below, the nanometer and nanosecond are the appropriate measures instead.

Do we really need nanocomputers? After all, you have to be able to see the screen and press the keys even if the processor is microscopic. The answer to this question lies in realizing just how closely economics and technological constraints determinewhat computers are used for. In the mid-sixties, IBM sold a small computer for what was then the average price of a house. Today, single-chip micros of roughly the same computational power cost less than $5 and are used as controllers in toaster-ovens. Similarly, we can imagine putting a nanocomputer in each particle of pigment to implement "intelligent paint", or at each pixel location in an artificial retina to implement image understanding algorithms.

This last is a point worth emphasizing. With today's processing technology, robots operating outside a rigid, tightly controlled environment are extremely expensive and running at the ragged edge of the state of the art. Even though current systems can, for example, drive in traffic at highway speeds, no one is going to replace truck drivers with them until their cost comes down by some orders of magnitude. Effective robotics depends on enough computational power to perform sensory perception; nanocomputers should make this cost-effective the way microcomputers did text processing.

Beyond providing robots with the processing power humans already have, there is the opportunity of extending those powers themselves. Nanocomputers represent enough power in little enough space that it would make sense to implant them in your head to extend your sensorium, augment your memory, sharpen your reasoning. As is slowly being understood in the world of existing computers, the interface to the human is easily the most computationally intensive task of all.

Last but not least – in some sense, the most important application for nanocomputers – is as the controllers for nanomechanical devices. In particular, molecular assemblers will need nanocomputers to control them; and we will need assemblers to build nanocomputers. (In the jargon of nanotechnology, an "assembler" is a robot or other mechanical manipulator small enough to build objects using tools and building blocks that are individual molecules.)

What is a nanocomputer?

Currently, the feature sizes in state-of-the-art VLSI fabrication are on the order of half a micron, i.e. 500 nanometers. In fifteen years, using nothing more than a curve-fitting, trend-line prediction, this number will be somewhere in the neighborhood of 10 nanometers; would it be appropriate to refer to such a chip as a nanocomputer?

For the purposes of this article, no. We want to talk about much more specific notions of future computing technology. First, we're expecting the thing to be built with atomic precision. This does *not* mean that there will be some robot arm that places one atom, then another, and so forth, until the whole computer is done. It means that the "design" of the computer specifies where each atom is to be. We expect the working parts (whether electrical or mechanical) to be essentially single molecules.

We can reasonably expect the switches, gates, or other embodiment of the logical elements to be on the order of a nanometer in size. (They may have to be further apart than that if electrical, due to electron tunneling.) In any case, it is quite reasonable to expect the entire computer to be smaller than a cubic micron, which contains a billion cubic nanometers.

Nanotechnology

The nanotechnology-assembler-nanocomputer dependence sounds like a self-referential loop, and it is. But many technologies are that way; machine tools make precision parts used in machine tools. Bootstrapping into a self-supporting technology is not a trivial problem, but it's not an impossible one either.

Another self-referential loop in nanotechnology is slightly more complicated. We would like assemblers to be self-reproducing. This would allow for nanocomputers and other nanotechnological products to be inexpensive, be-

cause each fixed initial investment would lead to an exponentially increasing number of nanomechanisms,
rather than a linearly increasing number.

But how can a machine make a copy of itself? The problem is that while we can imagine, for example, a robot arm that can screw, bolt, solder, and weld enough to assemble a robot arm from parts, it needs a sequence of instructions to obey in this process. And there is more than one instruction per part. But the instructions must be embodied in some physical form, so to finish the process, we need instructions to build the instructions, and so on, in an infinite regress. The answer to this seeming conundrum was given mathematically by John von Neumann, and at roughly the same time (the '50's) was teased out of the naturally occurring self-reproducing machines we find all around us, living cells. It turns out to be the same answer in both cases.

First, design a machine that can build machines, like the robot arm above. (In a cell, there is such a thing, called a ribosome.) Next, we need another machine which is special purpose, and does nothing but copy instructions. (In the cell it's called a replisome.) Finally, we need a set of instructions that includes directions for making both of the machines, plus whatever ancillary devices and general operating procedures may be needed. (In the cell, this is the DNA.) Now we read the instructions through the first machine, which makes all the new machinery necessary. Then we read it through the second machine, which makes a new set of instructions. And there's our whole new self-reproducing system, with no infinite regress.

General computer principles

When you get right down to it, a computer is just a device for changing information. You put in your input, and it gives you your output. If it's being used as the controller for anything from a toaster to a robot, it gets its input from its sensors and gives its output to its motors, switches, solenoids, speakers, and what have you.

Internally, the computer has a memory, which is used to store the information it's working on. Many functions, even so simple as a push-on, push-off lightswitch, need memory by definition. But the computer also uses memory to help break the job down to size, so as to be able to change the data it receives in little pieces, one at a time. The more memory you allow, and the smaller the pieces, the simpler the actual hardware can be.

There is a "folk theorem" in the computer world that the NAND gate is computationally universal. This is true in the sense that one can design any logic circuit using only NAND gates. However, something much more surprising is also true. Less than ten years ago, Miles Murdocca, working at Bell Labs, showed (in an unpublished paper) how to build a universal computer using nothing but delay elements and *one single OR gate.* Just one. Not circuits using arbitrarily many of just one kind of gate.

Murdocca's computer works by driving the notion of a computer to its very barest of essentials. A computer is a memory and a device to change the information in the memory. Generally we add two more specifics: The information is encoded and changed under the rules of Boolean logic; and the changes happen in synchronized, discrete steps. To build a computer, then, we need some way to remember bits; some way to perform boolean logic; and some way to clock the sequence of remember, perform, remember, perform, etc.

In computers from historical times to date, information has been encoded either as the position of a mechanical part, the voltage on a wire, or a combination (as in a relay-based computer). The major reason is that these are the easiest encodings to use in the logic part of the particular technology in question. It seems reasonable to expect to see these encodings at the nano level, for the same reasons.

Additional constraints for nano-computers

About a year ago I had the occasion to design a nano-computer using Eric Drexler's mechanical rod logic, which will be examined in detail later in this article. As someone who was used to the size and speed constraints of electronics, I was in my glory with this new medium. I went wild, adding functionality, pipelining, multicomputing, the works. I could build a super-computer beyond the wildest dreams of Cray, the size of a bacterium! What I *didn't* do was pay any attention to "this crazy reversible computing stuff."

— Until I did the heat dissipation calculations. The problem is that there really is a fundamental physical limit involved in computation, but it represents an amount of energy so small (it's comparable to the thermal energy of one atom) that it is totally negligible in existing physical devices. But in a nanocomputer, it far outweighs all the other heat-producing mechanisms; in fact, my nanocomputer design had the same heat dissipation per unit volume as a low-grade explosive. Back to the drawing board...

Since the earliest electronic computers in the 1940's, energy dissipation per device has been declining exponentially with time. Device size hasundergone a similar decline, with the result that overall dissipation per unit volume has been relatively constant (see the horizontal bar in Fig. 1). Historically, the portion represented by the thermodynamic limit for irreversible operations was completely insignificant; it is still in the parts per million range. However, with densities and speeds in the expected range for nanocomputers, it is extremely significant. Thus nanocomputer designers will be forced to pay attention to reversibility.

Efficient computers, like efficient heat engines, must be as nearly reversible as possible. Rolf Landauer showed in a landmark paper (in 1961) that the characteristic irreversible operation in computation is the erasure of a bit of information; the other operations can be carried out in principle reversibly and without the dissipation of energy. And as in heat engines, the reason reversibility matters is the Second Law of Thermodynamics, the law of entropy.

Entropy

The subject of entropy seems to give rise to more misconceptions and disagreements than any other scientific principle. Relativity and quantum mechanics have been similarly abused, but much of the abuse is in the form of extensions of the concepts that are frankly metaphorical. Relativity and quantum mechanics do not, in general, apply to the everyday world, but entropy does. When people use metaphorical extensions of entropy on phenomena that are governed by actual entropy, confusion occurs.

It's possible, on the other hand, to give a metaphorical explanation of entropy that is carefully rigged to give all the same answers as actual entropy. Here it is; but if you'd prefer to take my word for it that nanocomputers *must* be reversible, you can skip to the next section.

Let us suppose that we are going to have a computer simulation of some closed physical system. We can have as high an accuracy as we like, but the total amount of information, i.e. the number of bits in the computer's memory, is in the end some fixed finite number. Now since the physical system we're simulating is closed, there will be no input to the simulation once it is started.

Since there is a fixed number of bits, say K, there is a fixed number of possible descriptions of the system the simulation can ever possibly express, namely 2^K of them. Now by the first law of thermodynamics, conservation of energy, total energy in a closed system is constant. Thus we can pick all of the states with a given energy, and call them "allowable", and the rest are forbidden. The first law constrains the system to remain within the allowable subset of states but says no more about which states within that set the system will occupy.

There is another constraint, however, in the sense that the laws of physics are deterministic; given a state, there is a single successor state the system can occupy in the next instant of time. (In the real world, this is more complicated in two ways: Time and the state space are continuous, and quantum mechanics provides for multiple successor (and predecessor) states. However, the mathematical form of quantum mechanics (i.e. Hamiltonian transformations) gives it properties analogous to the the model, so for perspicuity, we will stick with the discrete, deterministic model.) What is more, the laws are such that each state has not only a unique successor, but a unique predecessor.

Let's try to make this notion a little more intuitive. Each "state" in our computer simulation corresponds to some description of all the individual atoms in the physical system. For each atom, we know exactly where it is, exactly how fast it is going, exactly in what direction, etc. As we move forward in time, we can calculate all the electrical, gravitational, and if we care, nuclear, forces on that atom due to all the other atoms, and compute just where it will be some tiny increment of time in the future. Clearly, to just the same degree of precision, we can calculate exactly where it must have been the same tiny amount of time in the past. The math of the physical laws allow you to simulate going backwards just as deterministically as you can simulate going forwards.

So, suppose we have a simulation of a box which has a partition dividing it in half. There is some gas in one half, i.e. atoms bouncing around, and none in the other. Now suppose the partition disappears: the atoms that would have bounced off it will continue on into the empty half, which pretty soon won't be empty any more. The atoms will be distributed more or less evenly throughout the box.

What happens if we suddenly stop the simulation and run it backwards? In fact, each atom will retrace the exact path it took since the partition disappeared, and by the time the partition should reappear, the atoms will all be in the original half.

In reality, we don't see this happen. Remember that in our model there is a distinct causal chain of states from the state where the atoms are all spread out but about to move into half the box, to the state where they are actually in half the box. This means that the number of states from which the atoms are about to compress spontaneously (in some specific number of timesteps) is the same as the number of states in which they are all in one half of the box.

The important thing to remember is that the total energy (which is proportional to the sum of the squares of the velocities of the atoms) must be the same. If we used a simulated piston to push the atoms back into the original half, we would find a 1-to-1 mapping between spread-out states and compressed ones; but the compressed ones would be higher-energy states.

How many states are we talking about here? Well, suppose that all we know about any specific atom is which side of the box it is in, which we can represent with a single bit. If the box has just 100 atoms in it, there will be more than 1,267,000,000,000,000,000,000,000,000,000 states in which the atoms are spread around evenly, and one state where they are all on one side. A similar ratio holds between the number of states (with full descriptions) where the atoms are spread-out, and the subset of those states where they are about to pile over into one side.

It's clear that quantum mechanics allows for mechanisms that capture a single electron and hold it reliably in one place. Individual electrons doing specific, well-defined things under the laws of quantum mechanics is what happens in typical chemical reactions... there is no basic physical law that prevents us from building nanocomputers that handle electrons as individual objects.

We are now going to talk about entropy. In order to relate the simulation model of a physical system to the way physical scientists view physical systems, we'll use the term "microstate" to represent what we have been calling a state in the simulation, i.e. one specific configuration of the system where all the bits are known. We'll use "macrostate" to refer to what a physical scientist thinks about the system. This means knowing the temperature, pressure, mass, volume, chemical composition, physical shape, etc, but not knowing everything about every atom.

Clearly, there are lots of microstates in a macrostate. The log of the number of microstates in a given macrostate is the entropy of the macrostate. (Physical entropies are generally given as natural logs, but we will talk in terms of base 2 logs with the understanding that a scaling factor may be needed to translate back.) To put it more simply, the entropy of a given macrostate is the number of bits needed to specify which of its microstates the system is actually in.

With these definitions, the second law of thermodynamics is quite straightforward. If a proposed physical transformation maps a macrostate with a higher entropy into one with a lower entropy, we know it is impossible. Remember the causal chains of (micro)states: they can neither branch nor coalesce. Now suppose at the beginning of some physical process, the system was in a macrostate with a trillion microstates; we have no idea which microstate, it could be any one of them. Therefore at the end of the process, it can still be in a trillion microstates, each at the end of a causal chain reaching back to the corresponding original microstate. Obviously, the system cannot be in any macrostate with fewer than a trillion microstates, i.e. with a lower entropy than that of the original macrostate.

Now suppose I have a beaker of water at a specific temperature and pressure. It has, according to a physicist or chemist, a specific entropy. But suppose I happen to know a little more about it, e.g. I have a map of the currents and vortices still flowing around in it from when it was stirred. There are a lot of the microstates that would be allowed from the simpler description, that I know thewater is not really in. Isn't its entropy "really" lower? Who gets to say which is the "real" macrostate, whose size determines the "true" entropy of the system?

The answer is, that entropy isn't a property of the physical system at all, but a property of the description. After all, the real system is only in one single microstate! (Ignoring quantum mechanics.) This does sound a bit strange: Surely the "true" entropy of any system is then 0. And we should be able to induce a transformation from this system into any macrostate we like, even one with much lower entropy than that of the original macrostate of the system as conventionally measured.

Let's consider the little box with the atoms of gas in it. The gas is evenly spread through the box, a partition is placed, and there is a Maxwell's Demon with a door to let the atoms through selectively. But the demon isn't going to try anything fancy. We're going to assume that we know the exact position and velocity of each atom in advance, so we will be able to provide the demon with a control tape that tells him when to open and close the door *without observing the atoms at all*. In fact, this would work; the demon can herd all the atoms into one side without expending any energy.

Why doesn't this violate the second law? Well, let's count up the causal chains. The entropy problem in the first place is that there are many many fewer microstates in the final macrostate, namely the one with all the atoms on one side, than in the original, so that many original microstates must somehow map into a single final one. But with the demon at work, we can run the simulation backwards by running the demon backwards too; the sequence of door-opening and closing that got us to our particular final microstate is clearly enough information to determine which original microstate we started from. Thus the final state, *including the tape*, is still in a one-to-one mapping with the original state, and the second law is not violated.

The curious thing to note about this gedanken experiment is that the demon *can* compress the gas without expending energy; what he *cannot* do is erase the tape! This would leave the system with too few final states.

What happens if the demon starts with a blank tape, instead of one where the microstate of the system is already recorded? Can he measure the system on the fly? Again yes, but only if he writes his measurements on the tape. Again the critical point is that the data on the tape serves to make the number of possible final microstates as large as the number of possible original microstates.

In practice, of course, the way one would obtain the same result, i.e. moving the atoms into half the box, would be to use a piston to compress the gas and then bring it in contact with a heat sink and let it cool back to the original temperature. Energy, in the form of work, is put into the system in the first phase and leaves the system, in the form of heat, in the second phase. At the end of the process the system is the same as the demon left it but there is no tape full of information. Clearly there is some sense in which the dissipation of heat is equivalent to erasing the tape.

In terms of the simulation model, the demon directly removes one bit from the position description of each atom (storing it on the tape). The piston compression moves a bit from the position to the velocity description, and the cooling process removes that bit (storing it in the heat sink). The entropy of the gas decreases, and that of the heat sink increases.

Of course, dissipating heat is not the only way to erase a bit. Any process that "moves" entropy, i.e. decreasing it in one part of a system at the expense of another part, will do. For example, instead of increasing the temperature of a heat sink, we could have expanded its volume. Or disordered a set of initially aligned regions of magnetization (in other words, written the bits on a tape). Or any other physical process which would increase the amount of information necessary to identify the system's microstate. However, heat dissipation is probably the easiest of these mechanisms to maintain as a continuous process over long periods of time, and it is well understood and widely practiced.

A state-of-the-art processor, with 100,000 gates erasing a bit per gate per cycle, at 100 MHz, dissipates about 28 nanowatts due to entropy. (At room temperature. Each bit costs you the natural log of 2, times Boltzmann's constant, times the absolute temperature in Kelvins, joules of energy dissipation, which comes to about 2.87 maJ (milli-attoJoule, 10^-21 Joules)). Since it actually dissipates 100 million times this this much, or more, nobody cares. But with a trillion-fold decrease in volume and thousand-fold increase in speed, the nanocomputer is "a whole 'nother ball game."

Thus there are two new design rules that the nanocomputer designer must adopt:

(1) Erase as few bits as possible.
(2) Eliminate entropy loss in operations that do not erase bits.

We eliminate entropy loss in logical operations by what is known as "logical reversibility". Suppose we have in our computer registers A and B, and an instruction ADD A,B that adds A to B. Now in ordinary computers that would be done by forming the sum A+B, erasing the previous contents of register B, and then storing the sum there. However, it isn't logically necessary to do this; since we can recreate the old value of B by subtracting A from the new value, no information has been lost, and thus it is possible to design a circuit that can perform ADD A,B *without* erasing any bits.

Addition has the property that its inputs and results are related in such a way that the result can replace one of the inputs with no loss of information. However, many useful, even necessary, functions don't have this property. We can still use those functions reversibly; the only trick needed is not to erase the inputs! Ultimately, of course, you have to get rid of the input in order to process the next one; but you can *always* erase the *output* without entropic cost if you've saved the input.

This leads to structures in reversible computation called "retractile cascades." Each of a series of (logical) circuits computes a function of the output of its predecessor. If the final output is erased first, and then the next-to-last, and so forth, the entire operation is reversible, and can be done (in theory!) without any energy dissipation.

If we adopt these rules throughout our computer design, we can reduce the number of bits erased per cycle from around 100,000 to around 10.

Drexler's mechanical logic

K. Eric Drexler, "the father of nanotechnology", has designed and subjected to a thoroughgoing analysis, a *mechanical* logic for nanocomputers. A mechanical logic has the disadvantage of being slower than an electronic one, but has the major advantage that at the molecular level it is possible to design, and analyse the operation of, a mechanical logic with current molecular simulation software, and be reasonably certain that the design, if built, would work.

By the time we get around to actually building molecular computers, our analytical tools will be better than they are now, and what's more we'll be able to augment the simulations with physical experiments. So real nanocomputer designs won't have to be nearly so conservative as this one. In particular, they'll probably be electronic, and thus probably some orders of magnitude faster. But don't worry: this mechanical design is already plenty fast.

This formulation is sometimes called "rod logic" because instead of wires, it uses molecular-sized rods. (E.g. a nanometer in diameter and from ten to a hundred nanometers long.) Each rod represents a logic 0 or 1 by its position, sliding slightly along its length to make the transition.

To do logic, the rods have knobs on them which may or may not be blocked by something, preventing the rod from changing state. The "something" is simply other knobs on other rods, which block or don't block the first rod, depending on *their* state. (see Fig. 2) The logic is clocked by pulling on rods through the equivalent of a spring, so that it moves unless blocked. (We can draw a workable parallel to transistors, which block or don't block a clock from changing the voltage on a wire, depending on the voltage of another wire.)

The rods move in a fixed, rigid housing structure which might be thought of as a hunk of diamond with appropriate channels cut out of it (although it wouldn't be built that way). The rods are supported along their entire length so the blocking does not place any bending stress on them.

Any logic function is now simply constructed: for an AND gate, for example, take two input rods and place knobs so that they block the output rod when they are in the "0" position. The output rod will only be able to move to the "1" when both inputs are "1."

(Now that we can build a single gate, aren't we just about finished, by virtue of Murdocca's design? Well, we'd still need clocking and some mechanism to handle a delay-line memory; but more to the point the design produces a computer that is about a billion times slower than you could build with conventional logic designs!)

The motion of the rods is limited by the speed of sound (in diamond); but they are so short (e.g. one-tenth of a micron) that the switching times are still a tenth of a nanosecond. The speed of an entire nanocomputer of this kind of design will be limited by thermal noise and energy dissipation, which can produce enough variation in the shapes of the molecular parts to keep them from working right. Drexler gives a detailed analysis of the sources of such error in *Nanosystems* (chapter 12). The energy dissipated per switching operation is conservatively estimated at about 0.013 maJ.

This is less than 5% of the fundamental limit for bit destruction; as long, of course, as the gate in question doesn't destroy bits! Most of the logic design in a rod logic nanocomputer *must* be either conservative logic or retractile cascades. To demonstrate the difference, consider a NOT gate. One can implement a conservative NOT because it has an exact inverse (which happens to be itself). One could implement a conservative NOT in rod logic with a single gear meshing with racks on input and output rods. A retractile NOT on the other hand would be a single rod crossing with knobs preventing the output from moving to "1" if the input was "1". The "retractile" part is that the output must be let back down easy, in such a way that the energy stored in the spring is retrieved, before the input is reset for the next operation.

If this is not done, e.g. if the input is released first, the output rod will return under force of its spring and the energy stored in the spring will be dissipated as heat. In order for this not to happen, the output rod must be returned first, and then the input may be.

One very powerful and widely used technique in logic design is called the PLA (programmed logic array). A PLA is readily designed in retractile cascade style; it also has a remarkably good match to the geometric constraints of the rod logic, which requires the input and output rods from any interaction to form a right angle. The PLA consists of three sets of rods: the inputs, the minterms, and the outputs (see Fig. 3). First the input rods are moved, i.e. set to the input values. Then the minterm rods are pushed; some of them move and some don't depending on which inputs blocked them. In an electronic PLA each input is both fed directly into these interactions, and its negation is; this need not be done in the rod logic since its effect can be had by altering the position of the knobs. Sometimes the number of minterms can be reduced for the same reason.

After the minterm rods are pushed, the output rods are pushed, and the appropriate value is encoded in which ones actually move. Now, the important thing in preserving reversibility (what makes this a retractile cascade) is that after this operation, first, the output rods must be let back down gently; then the minterms let back down gently; and finally the inputs can be released.

Notice that in the figure, the input rods are at rest in the 0 position, while the output rods are at rest in the 1 position. (And in any given operation, exactly one of the minterm rods will slide to the left.)

PLA's can implement any logic function necessary in a computer, although there are more efficient circuits for some of them that are commonly used instead. More crucial, however, to a full grasp of the mechanisms of a nanocomputer, is memory.

Registers and memory

Memory is a problem; if we follow the rules for conservative or retractile reversible logic, memory is impossible to implement. This is because any memory with a "write" function erases bits *by definition.*

In Drexler's rod-logic design, all the bit-erasing functionality is concentrated in the registers. The register design is fairly complex, to keep the energy dissipated in this process near its theoretical minimum.

The main problem is that for a physical system to retain one of two states reliably, which is what you want in a memory, there must be a potential barrier between the states that is significantly higher than kT, or thermal fluctuations will be sufficient to flip the bit at random. But in simple implementations, the height of the barrier determines how much energy is lost when the system changes state.

Consider an ordinary light switch. When you flip it, there's a spring that resists your finger until the halfway point, and then it snaps into place, dissipating all the energy you put into it as heat, vibration, and sound. (A "silent" switch is worse, since it dissipates by friction and you have to push all the way across.) The weaker the spring, and the more likely that some vibration will flip the switch when you didn't intend it. The trick is to have some way to change the strength of the spring (or to have the effect of doing so).

In Figure 4, there is a simplified version of Drexler's register. The bit it contains is reflected in the position of the shaded ball (In the real design it's more complicated so that the value can be read!). (a) and (b) show the register when it contains 0 and 1 respectively. In (c), the barrier has been lowered and the ball is free to wander freely between both positions; this stage increases entropy. In (d), the register is reset to 0. The similarity to compressing a gas-filled cylinder is apparent; this is where ln(2) kT joules of work are converted into heat. Now to write the next bit, the input rod (on the right) is either extended (a 1, see (f)) or not (a 0, see (e)) and then the barrier raised. Finally, the spring rod (on the left) is retracted to get back to (a) or (b). If a 1 was written, the input rod did work to compress the ball into the spring, but that energy can be retrieved when the spring rod is retracted. The mechanisms to do this are just the same as in the logic portions, e.g. having the rods mechanically coupled to a flywheel.

Registers like this which are going to be used to erase bits will tend to be located near heat sinks or coolant ducts; bit erasure is the largest component of power dissipation in the rod logic design. Memory can be implemented as lots of registers; registers occupy about 40 cubic nanometers per bit. Thus about 3 megabytes worth of registers fill a cubic micron. One would probably use register memory for cache, and use a mechanical tape system for main storage, however. The "tape" would be a long carbon chain with side groups that differed enough to be 1's and 0's. Since the whole computer is mechanical, the difference in speeds is not as bad as macroscopic tapes on electronic computers. Such a tape system might have a density inthe neighborhood of a gigabyte per cubic micron. Access times for using a tape as a random access memory consist almost entirely of latency; if the length of individual tapes is kept to under 100 kbytes, this is in the 10's of microseconds.

Motors

In order to drive all this mechanical logic we need a motor of some kind; Drexler has designed an electric motor which is nothing short of amazing. (Clearly this is of import well beyond computers.) The reason is that the scaling laws for power density are in our favor as we go down toward the nanometer realm. At macroscopic sizes, almost all electric motors are electromagnetic; at nano scales, they will be electrostatic. The motor is essentially a van de Graff generator run in reverse (but it works just fine as a generator, as do some macroscopic electric motors). The power density of the motor is over 10^15 W/m^3; this corresponds to packing the power of a fanjet from a 747 into a cubic centimeter. (It's not clear what you'd *do* with it if you did, though!)

Ultimately, the ability to make small, powerful motors is going to be more important for nanorobots than nanocomputers per se. The speed advantage of electronics over mechanical logic is almost certain to drive the descent into nanocomputer design.

Other logics for nanocomputers

Before going into other extensions of conventional digital logic, there is another form of nanocomputer that may appear earlier for technological reasons. That's the molecular biocomputer.

Imagine that a DNA molecule is a tape, upon which is written 2 bits of information per base pair (the DNA molecule is a long string of adenine-thymine and guanine-cytosine pairs). Imagine, in particular, this to be the tape of a Turing machine, which is represented by some humongous clump of special-purpose enzymes that reads the "tape," changes state, replaces a base pair with a new one, and slides up and down the "tape." If one could design the enzyme clump using conventional molecular biology techniques (and each of the individual functions it needs to do are done somewhere, somehow, by some natural enzyme) you'd have a molecular computer.

Other mechanical logics

Now, back to mechanical logic. Most macroscopic mechanical logic in the past has typically been based on rods that turned instead of sliding. It's reasonable to assume that similar designs could be implemented at the nano scale.

Electronic logic

It's clear that quantum mechanics allows for mechanisms that capture a single electron and hold it reliably in one place. After all, that's what an atom is. Individual electrons doing specific, well-defined things under the laws of quantum mechanics, is what happens in typical chemical reactions. Clearly there is no basic physical law that prevents us from building nanocomputers that handle electrons as individual objects.

What is not so clear is how, specifically, they will work. Quantum mechanics is computationally very expensive to simulate, and intuitively harder to understand, than the essentially "physical object" models used in mechanical nanotechnology designs thus far. Indeed, the designs are typically larger and slower than they would have to be in reality, simply to avoid having to confront the analysis of quantum effects.

Ultimately, however, nanotechnologists will be "quantum mechanics." Computers based on quantum effects will be even smaller, more efficient, and much faster than mechanical ones of the type presented above. They will use much the same logical structure: it's quite possible to design retractile cascades even in conventional transistors (where it's an extension of techniques called "dry switching" in power electronics and "hot clocks" in VLSI design).

There are schemes, with some mathematical plausibility, to harness quantum state superposition for implicit parallel processing. In my humble opinion, these will require some conceptual breakthrough (or at the very least, significant experimental clarification) about the phenomenon of the collapse of the Schroedinger wavefunction before they can be harnessed by a buildable device. Keep your fingers crossed!

Conclusion

Beyond certain rapidly approaching limits of size and speed, *any* computer must use use logical reversibility to limit bit destruction. This is particularly true of nanocomputers with molecular-scale components, which if designed according to standard current-day irreversible techniques, explode.

We can design nanocomputers today which we are virtually certain would work if constructed. They use mechanical parts that are more than one atom but less than ten atoms across in a typical short dimension. The parts move at rates of up to ten billion times per second; processors built that way could be expected to run at rates of 1000 MIPS. Such a processor, and a megabyte of very fast memory, would fit in a cubic micron (the size of a bacterium). A gigabyte of somewhat slower memory would fit in another cubic micron. A pile of ten thousand such computers would be just large enough to see with the naked eye.

FURTHER READING

Drexler, K. Eric: *Nanosystems: Molecular Machinery, Manufacturing, and Computation,* Wiley Interscience, New York, 1992

Proceedings of the Physics of Computation Workshop, Dallas, October 1993: IEEE Press, (in press). (particularly papers by Merkle, Hall, and Koller)

Hennessy, J.L. & Patterson, D.A.: *Computer Architecture: A Quantitative Approach,* Morgan Kaufmann, San Mateo, CA, 1990

Watson, Hopkins, Roberts, Steitz, & Weiner: *Molecular Biology of the Gene,* Benjamin/Cummings, Menlo Park, CA, 1987 (4th ed.)

Leff, Harvey S. and Andrew F. Rex: *Maxwell's Demon: Entropy, Information, Computing,* Princeton University Press, Princeton, NJ, 1990 (Particularly papers by Landauer and Bennett)

EXTROPY INSTITUTE

Why an Extropy Institute?

Fundamentally, two related reasons led us to form Extropy Institute (ExI) out of the persons and forces attracted by the intellectual gravitation of *Extropy* magazine. The first objective was to draw together people of shared values and goals, to act as focal point – a nexus – to facilitate their interaction, mutual aid, and exchange of information. I saw ExI as the nucleating agent which would crystallize a fresh, dynamic culture to sustain those who find themselves alienated from the surrounding society's bizarre religious, political, and intellectual practices, institutions, and beliefs.

I defined the Extropian Principles of Boundless Expansion, Self-Transformation, Dynamic Optimism, Intelligent Technology, and Spontaneous Order to give shape to the vision of life I shared with Tom Morrow, co-founder of *Extropy*. The Extropian culture grows rapidly as many others encounter a life-stance which explicitly interrelates their own values and goals, including political individualism and voluntarism, personal responsibility, rationality, skepticism, enthusiasm for technology, a desire for perpetual self-improvement, and an urge to overcome historical, cultural, biological, genetic, neurological, and spatial limits, including many that most humans rarely think to question, such as the process of aging and dying.

The second, closely related purpose of ExI, is educational. By gathering and focusing the energies of transhumanists all over this planet, we seek to shift cultural attitudes in an extropic direction, both by persuasion and by personal example. We will encourage the more traditional, uncritical, and timid members of our species to doubt both the desirability and inevitability of death and taxes, to outgrow irrationalist and mystical religions, and to challenge every limit to our potential. ExI promulgates a philosophy of life appropriate for rational persons rushing headlong into a future of boundless possibility, where many of the rules of existence will be changed.

ExI Membership

Following incorporation in May 1992, ExI began to offer memberships in June 1992, and has been growing strongly since. Members receive *Extropy: The Journal of Transhumanist Thought* – the central source of extensive intellectual exploration. In addition, members receive the bi-monthly newsletter, *Exponent* (edited by Simon! D. Levy). *Exponent* provides regular news updates, shorter writings, book, movie, and software reviews of Extropian interest, reports on crucial advances in science, and provides information on meetings and electronic gathering places.

ExI members receive discounts, currently on T-shirts and audio tapes, and later on books, software, and events.

We are in the early information gathering stages of organizing the first International Extropy Institute Conference, likely to be held in 1994. The conference will draw together top-flight brains in many fields for a unique and intense round of lectures, panel discussions, and social events.

The Extropian network grows as individuals organize local meetings, both social and purposive. The first gatherings in Los Angeles in 1991, have been followed by meetings in New York, San Francisco, and Boston.

Members and non-members alike can dive into prolific discussions across the Internet (see back cover for details). The main Extropians list, managed by Harry Shapiro, is a torrent of fascinating discussion, its overwhelming volume now tamed by the addition of a digest version, thanks to Ray Cromwell. There are several email lists for local organization, and an essay list for extensive original essays. Thanks to the ease of communication granted by a modem and the Internet, a flourishing Extropian virtual community has arisen over the past 17 months since ExI member Perry Metzger originally created the Extropians list.

Further information on our other proposed projects can be found in the last issue of *Extropy*. The ambitious roster of projects found there should be understood as a prospectus for our future, not a description of our current status. Extropy Institute is yet a newborn, without wealhy parents. Yet ExI grows and develops vigorously. Join us, and fly upward and outward with us as we take charge and *create* the future we seek to inhabit.

Max More, Executive Director, ExI

Ten Books

The dauntingly long list of books following the Extropian Principles 2.0 (see *Extropy* #9) may deter some from even starting to read these mind-expanding works. So, acting on a suggestion by Mark Plus, here are the ten books that I believe serve jointly to explain much of the Extropian conception of self and universe, in the past, present, and probable future.

Paul M. Churchland, *Matter and Consciousness*.
Richard Dawkins, *The Selfish Gene*.
K. Eric Drexler, *Engines of Creation*.
David Friedman, *The Machinery of Freedom*.
Hans Moravec, *Mind Children: The Future of Robot and Human Intelligence*.
Ed Regis, *Great Mambo Chicken and the Transhuman Condition*.
Julian L. Simon, *The Ultimate Resource*.
Robert Anton Wilson, *Prometheus Rising*.
Ayn Rand, *Atlas Shrugged*.
Marc Stiegler, *The Gentle Seduction*.

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#9, Vol.4 No.1 (Summer 1992):

The Extropian Principles, 2.0, by Max More; Extropy Institute Launches, by Max More; Persons, Programs, and Uploading Consciousness, by David Ross; Nanotechnology and Faith, by J. Storrs Hall; The Making of a Small World (fiction), by R. Michael Perry; Genetic Algorithms, by Simon! D. Levy; Time Travel and Computing, by Hans Moravec; Futique Neologisms 3; Exercise and Longevity, by Fran Finney; The Transhuman Taste (Reviews): *The Anthropic Cosmological Principle*, *The Blind Watchmaker*, *The Ultimate Resource, Population Matters, The Resourceful Earth*, *Bionomics*

#8 Vol.3 No.2 (Winter 1991-92):

Idea Futures: Encouraging an Honest Consensus, by Robin Hanson; Dynamic Optimism, by Max More; Neurocomputing 5: Artificial Life, by Simon! D. Levy; Futique Neologisms (futurist lexicon); Extropia: A Home for Our Hopes, by Tom Morrow; Human-Transhuman-Posthuman, by Max More; Reviews of: Stiegler's *David's Sling*, Drexler's *Unbounding the Future*, Platt's *The Silicon Man*; News of scientific advances and movement news; Reviews of zines.

#7 Vol.3 No.1 (Spring 1991):

A Memetic Approach to 'Selling' Cryonics, H. Keith Henson & Arel Lucas; Privately Produced Law, Tom Morrow; Order Without Orderers, Max More; Futique Neologisms; Neurocomputing 4: Self-Organization in Artificial Neural Networks, by Simon! D. Levy; Forum on Transhumanism; Reviews of *Smart Pills*, *Surely You're Joking Mr Feynman*, *Great Mambo Chicken and the Transhuman Condition*; and more...

#6 (Summer 1990):

Transhumanism: Towards a Futurist Philosophy, by Max More; The Thermodynamics of Death, Michael C. Price; The Opening of the Transhuman Mind, by Mark Plus; The Extropian Principles, by Max More; Neurocomputing Part 3, by Simon! D. Levy; Forum on Arch-Anarchy and Deep Anarchy; Reviews: *Order Out of Chaos*, *The Emperor's New Mind*, *A Neurocomputational Perspective, Loompanics Greatest Hits, The Machinery of Freedom*; Extropian Resources, and more.

#5 (Winter 1990):

Forum: Art and Communication; Leaping the Abyss, by Gregory Benford; Arch-Anarchy, by A; Deep Anarchy, by Max O'Connor; I am a Child, by Fred Chamberlain; Perceptrons (Neurocomputing 2), by Simon D. Levy; On Competition and Species Loss, by Max O'Connor; A Review of *Intoxication*, by Rob Michels; Intelligence at Work, by Max O'Connor and Simon D. Levy; Extropian Resources, by Max O'Connor and Tom W. Bell; The Extropian Declaration, by Tom W. Bell and Max O'Connor; Our Enemy, 'The State,' by Max O'Connor and Tom W. Bell

#4 (Summer 1989):

Forum; In Praise of the Devil, by Max O'Connor; Neurocomputing, by Simon D. Levy; Why Monogamy? by Tom. W. Bell; What's Wrong With Death? by Max O'Connor; Reviews: *Are You a Transhuman?* Postscript to "Morality or Reality" by Max O'Connor; Efficient Aesthetics, by Tom. W. Bell; Intelligence at Work: Advances in Science by Max O'Connor

#2 (Winter 1989):

Review of *Mind Children,* by Max O'Connor; Darwin's Difficulty, by H. Keith Henson and Arel Lucas; A Truly Instant Breakfast, by Steven B. Harris M.D.; Wisdomism, by Tom W. Bell; Nanotechnology News, by Max O'Connor; Weirdness Watch, by Mark E. Potts

#1 (Fall 1988):

A brief overview of extropian philosophy and an introduction to some of the topics we plan to address: AI, Intelligence Increase Technologies, Immortalism, Nanotechnology, Spontaneous Orders, Psychochemicals, Extropic Psychology, Morality, Mindfucking, Space Colonization, Libertarian Economics and Politics, Memetics, and Aesthetics; "Morality or Reality," by Max O'Connor.

#3 (Spring 1989) is out of print.

Beyond the poor man's Extropianism: A review of two books about Ayn Rand and Objectivism.

by Mark Plus

(A) *Atheism, Ayn Rand, and Other Heresies*, by George H. Smith. (Buffalo, New York: Prometheus Books, 1991). 324 pages. ISBN 0-87975-577-6.

(B) *The Ideas of Ayn Rand*, by Ronald E. Merrill. (La Salle, Illinois: Open Court, 1991). 191 pages. ISBN 0-8126-9157-1.

Introduction

The Extropian eupraxophy, although currently associated with relatively few individuals, is an example of a spontaneous order. Rather than being presented as a completed intellectual system in the manner of, say, Thomas Aquinas, it is instead the open-ended confluence of ideas from many individuals and disciplines. A "fountainhead" of much Extropian thinking has been the late novelist-philosopher Ayn Rand, who, although succumbing to entropy in 1982, sketched out a philosophy, called Objectivism, which is compatible with the Extropian principles of Boundless Expansion, Self-Transformation, Intelligent Technology, Spontaneous Order, and Dynamic Optimism. (Indeed, her novel *Atlas Shrugged* is on the recommended reading list for "The Extropian Principles v. 2.0.")

Unfortunately Rand never developed the full extropic implications of her system. She has left her followers to make do with a bug-ridden "Objectivism 1.0," a kind of poor man's Extropianism. Hence Objectivism, although still a powerful eupraxophy, lacks the vigor and appeal it would have if certain errors were corrected and many Extropian features, e.g. immortalism, were explicitly expressed.

Fortunately in recent years a number of independent Randian scholars have been working on versions of "Objectivism 2.0," which, although falling short of full Extropianism, demonstrate attempts to grapple with the realities of tomorrow. These efforts have helped to ground Objectivism in the thought of the past, while preparing for its growth and improvement in the future. As this review will make clear, Objectivism must engage in Boundless Expansion to maintain its intellectual power. The two books under review describe these revisions.

(A) Objectivism's Heritage: Thomism without "God" (the G-word)

George H. Smith is an independent scholar who moves comfortably in both freethought and libertarian circles. His earlier book, *Atheism: The Case Against God*, has been a steady seller at Prometheus Books for over a decade, while during the same time he has been writing and lecturing in advocacy of libertarian ideas.

In his new book, *Atheism, Ayn Rand, and Other Heresies*, Smith combines his interests by grouping both freethought and libertarian essays together around the theme of "heresy." As Smith explains in his Introduction, heresy (from Greek *hairesis*, "choice") was originally a morally neutral disagreement with someone else's "right belief" or orthodoxy. When one ideological group attains political power, however, its orthodoxy defines heresy as evil and corrupting, giving the orthodox both the means and the incentive to persecute heretics. It is only in the open society, where everyone can freely associate and delimit his or her respective orthodoxy, that the heretic can live without fear of physical sanctions, although there may be moral and social sanctions instead.

Though most of Smith's essays are both readable and thought-provoking, of relevance to this review are the three essays in the middle section of the book dealing with Ayn Rand. Rand was certainly a heretic, especially in her uncompromising secularism. In his essay "Atheism and Objectivism," Smith points out that Rand's atheism offends conservatives who might otherwise be open to her philosophy. According to the traditional religious critique of atheism, rejection of belief in the g-word leads to all sorts of theoretical and practical disasters.

Ironically, as Smith demonstrates, there is a grain of truth in this criticism, though the religionists are right for the wrong reasons. Many philosophies promote atheism, but at unacceptable costs.

After analyzing different approaches to atheism, Smith discusses the various kinds of epistemological atheism, one of which is Objectivism. Most of these – Humean skepticism, logical positivism, linguistic analysis – reject theism as nonsensical, but for the same reason also jettison objective ethics, certainty, causality, and metaphysical speculation.

Objectivism, like the other epistemological critiques of theism, requires that the g-word be defined in an intelligible way, and then places the onus of proof upon the theist. Since no intelligible, nontrivial definition of the g-word has ever been produced, and no argument for the existence of the g-word has withstood analysis, Objectivism accepts atheism as the only rational possibility.

Where Rand differs from other atheistic philosophers, however, is that she is an Aristotelian, with Aristotle's conception of philosophy as a necessity for human life. Thus her philosophy is equipped for worldly success, unlike the other "stripped down" secular philosophies of modernity. This seems rather odd, for the majority of Aristotelians on the scene today, the Thomists — the Catholic intellectual heirs of Thomas Aquinas — are opposed to secularism. As Smith writes, "With Objectivism and Thomism we have two philosophical movements claiming Aristotle as their intellectual ancestor, but that are on opposite sides of the religious spectrum." In other words, although Smith does not phrase it in this way, Objectivism is a kind of Thomism without the g-word.

Smith maintains that Rand's "rejection of God does not stem from the limitation or distrust of reason, rather, it is in the name of reason that she rejects faith, mysticism, and belief in the supernatural." He then concludes in this essay:

> In short, the atheism of Ayn Rand is not destructive in the least. In rejecting God, Rand does not reject metaphysics, ethics, certainty, or the possibility of happiness. On the contrary, it is because Rand has so much positive value to offer that she considers atheism to be a comparatively minor issue.

Of course, from our perspective Rand would have offered a lot more if she had advocated – and practiced! – immortalism. This is a major defect of Objectivism 1.0. Nevertheless she deserves credit for promoting a secularism which is a radical improvement over the dreary atheistic philosophies of Marxism, existentialism, and secular humanism.

In his second Randian essay, "Ayn Rand: Philosophy and Controversy," Smith develops the Rand/Aquinas parallel further. He commits his own heresy by arguing that, although Rand was not well read in philosophy, many of her epistemological and ethical arguments are similar to those made by modern Aristotelians such as the Thomists, while her political philosophy is clearly derived from classical liberalism. The components of much of Rand's thought may be borrowed from others, or else independently reinvented, but the way she puts them together into one system gives Objectivism its freshness and vitality. By identifying the ancestors and antecedents of Objectivism, Smith can place it firmly in the context of Western philosophy, while showing that it is not that far out of the mainstream. Rand may be a heretic, but she is one with a familiar genealogy.

After documenting these similarities, Smith speculates about the future of Objectivism. He considers the "official" school, led by Leonard Peikoff (the "Randian Grand Inquisitor") to be brain dead, and argues that the future lies in the work of independent, "neo-Randian" philosophers such as David Kelly, Tibor Machan, Douglas Rasmussen, and others. (I had considered reviewing Leonard Peikoff's book, *Objectivism: The Philosophy of Ayn Rand*, but it is not comparable to the other two in quality. Under Peikoff's care, dogmatic Objectivism, following the example of its cousin Thomism, is hardening into a dead scholasticism.) However, these neo-Randians may not get much closer to Extropianism than Rand if they continue to accept the limitations of the human envelope. The book reviewed in section B, written by a neo-Randian not mentioned by Smith, implies a way beyond the human condition.

Finally, in the third essay, "Objectivism as a Religion," Smith deplores the tendency of many Objectivists to turn Randian ethics into a system of rules one has to follow, regardless of the consequences to one's happiness. As he argues, a rule-based ethics is essentially religious, whereas Rand's ethics is based on the idea of ethical standards, which one chooses not out of fear or guilt, but rather out of intellectual conviction. One can obey or disobey a rule, but it makes no sense to obey or disobey a standard. In the Objectivist ethics one follows a standard as a guide for attaining the goal of personal happiness. As Smith concludes in this final Randian essay:

> Whatever her errors, Ayn Rand struggled mightily against a religious view of morality, and she sought to place ethics on a rational foundation, free of any appeal to faith or force. Rand was a humanist in the best sense; for her, the happiness of the human being is the *summum bonum* of ethics.

Of course Rand, like her philosophical opponents, promoted a deathist concept of happiness. Beyond deathist eudaimonism lies the challenge of immortalist Dynamic Optimism.

(B) Objectivism's Future: The Trans-Randian condition

If George H. Smith can show Objectivism's place in the thought of the past, Ronald E. Merrill suggests and implies what Objectivism has to do if it wishes to reach for the future, even to the threshold of transhumanism.

I had not heard of Merrill until I read his book *The Ideas of Ayn Rand*, but I can now state without reservation that it is the most fascinating study of Rand's thinking I have yet encountered. Indeed, there is so much material in the book that I have trouble selecting what I want to review.

Like Smith, Merrill wishes to locate Rand and Objectivism in their historical context. Unlike the recent biographies of Rand, however, Merrill avoids the prurient details, and concentrates instead on the *ideas* of Ayn Rand, as the book's title says. He writes that he became a "Randroid" at fifteen after reading *Atlas Shrugged*, and was associated with the Nathaniel Branden Institute (NBI) for awhile back in the 1960's. Although he met some eccentric people, he never encountered the cape-wearing Rand cultists other critics of the NBI period have described.

The break between Rand and Branden in 1968 destroyed what could have otherwise become a powerful force for reason and freedom, but Rand nevertheless continues to exert a covert influence on American thinking. Her novels still sell in the hundreds of thousands annually (in what is otherwise an increasingly illiterate society), while many of her ideas, advocated without proper acknowledgement through "conservative" ideologues, are becoming more widely accepted. (For example, the "conservative" broadcaster Rush Limbaugh sounds Randian much of the time, except when he starts mouthing off about the g-word. As Smith explains in his book, Rand's atheism is an impediment to a general recognition of her legitimacy.) Her on-going popularity suggests that Rand's vision is timeless, a vision which Merrill tries to explain.

In Chapters 2 through 5, where Merrill discusses Rand's development as a writer, he makes it clear that he considers her to be a deep and complex literary artist. As she struggled to master English prose while trying to survive in her adopted country, Rand also struggled with and eventually overcame her devotion to the philosophy of Friedrich Nietzsche.

Although according to the "official" history Rand flirted with Nietzsche briefly as a young woman before inventing Objectivism, Merrill documents how Rand was still a Nietzschean in the 1930's when she wrote the first version of *We the Living*. Comparing the original novel with the version Rand "revised" in the 1950's shows that she felt embarrassed by the Nietzschean dialogue she had written in the 1930's. It was only in *The Fountainhead*, where Rand contrasted the Objectivist Howard Roark with the Nietzscheans Dominique Francon and Gail Wynand, that Rand was able to show her break with Nietzsche. By this time Rand had decided that true mastery over one's circumstances came not from wielding the whip over the common people, as Nietzsche taught and Wynand practiced, but rather from self-discipline exercised through intellectual and economic productivity, as shown in the life of Roark.

Finally in *Atlas Shrugged* Rand dramatizes the outlines of her mature philosophy. Merrill argues that Rand's critics have misrepresented or misinterpreted many of that novel's controversial passages (the train tunnel explosion, for example), and that a full exegesis of all of *Atlas Shrugged*'s plots, ideas, psychological insights, and symbolism has still to be done. (He describes one theory that Galt's strike is based on a Talmudic exegesis of the biblical story of the destruction of Sodom, whose inhabitants were guilty not of perversion, but of collectivism. Rand did come from a Jewish family, but I have seen no hard evidence that she ever used her heritage as a source of literary allusions.) Clearly there is more information encoded in *Atlas Shrugged* than either its admirers or its detractors have yet extricated.

After analyzing Rand's literary development, in Chapter 6 Merrill comes the meat of his subject, Rand's formal philosophical ideas. As Merrill argues, Rand carried on the tradition of the Greek sophists, the market intellectuals who sold their wisdom to all comers. This placed her in direct opposition to the Socratic tradition in philosophy, for Rand took an anti-skeptical and anti-relativistic approach to the fundamental issues. Philosophy is too important to be left as a game for the intellectual elite.

Starting with the essentials of Aristotle's metaphysics, Rand assumes that "existence is identity," thus relieving her of the burden of explaining ultimate origins. Her metaphysics form the "boundary conditions" of the rest of her philosophy, to borrow a metaphor from mathematics, which determine everything else that follows. From there Merrill describes how Rand's theory of concepts, building blocks of her epistemology, emphasizes understanding over proof. This has the unfortunate consequence of leaving us without epistemological guidance in a lot of areas – including, as it will be shown, in Rand's theory of ethics. Merrill laments that Rand never directed her mind towards the epistemological paradoxes raised by general relativity and quantum mechanics. (Since Merrill seems to be well read in both science and philosophy, why doesn't he try to solve these puzzles?) And as an example of the epistemological wilderness in which Rand has left us, he writes:

> It not infrequently occurs that we must choose between two theories. One theory, call it A, is internally self-consistent, but there are some experimental facts that contradict it. The other theory, call it B, is consistent with all the facts but contains internal contradictions. No better theory is currently available, but one must make decisions, and right now – to design a spacecraft, to plan a campaign against a deadly epidemic, to prevent an explosion in a refinery. One must act, and on the basis of one theory or the other. Which should be chosen, A or B? This in an epistemological problem. The solution is left as an exercise for the reader.

From an analysis of Rand's epistemology Merrill moves on to his attempt to state and then reformulate Rand's derivation of ethics ("ought" statements) from the facts of human nature ("is" statements). Ironically the above thought-experiment bears directly on one weakness in Merrill's reformulation, though he does not seem to be aware of it.

Merrill paraphrases the "Randian Argument" as follows:

i. Living beings, and only living beings, have values (goals).

ii. Man, being volitional, must choose his values.

iii. Values – goals – may be means to an end, but must lead to some ultimate end. An infinite chain of means leading to no final end would be meaningless and impossible.

iv. Life is an ultimate end, and furthermore it is the only possible ultimate end, the only "end in itself."

v. Therefore, the only meaningful or justifiable values a man can choose are those which serve to sustain his life.

The sticking point in this argument is the fourth premise, involving the concept of "ends in themselves." Merrill better defines this concept by quoting from other Objectivist writings to the effect that life is an end in itself in that it "is an ordered collection of activities, which are means to achieving an end, which is — simply those activities." He also disposes of the problem of competing ends in themselves by arguing that life is the necessary prerequisite to all other ends, so that it is the most important end in itself, regardless of whether ends in themselves exist.

Next Merrill shows how to derive ethical statements from the facts of reality by equating normative ought statements – e.g., "You ought always to tell the truth." – with operational ought statements – e.g., "You ought to format a new disk before attempting to write a file to it." — in a manner analogous to Einstein's equation of gravity with acceleration in General Relativity. If one accepts this approach, then "ethics reduces to a matter of engineering" and "Objectivist ethics ... can provide a prescription for any specified moral dilemma."

Unfortunately Merrill's reformulation of the Randian Argument suffers from its own problems. First of all, if one accepts the proffered definition of life as an end in itself, the fact remains that the activities of life lose their efficiency, and eventually break down, due to aging. It cannot be argued that aging is one of the activities of life one engages in today in order to repeat those activities tomorrow. Aging eventually destroys one's ability to engage in the activities of life. Hence one's life is a depreciating ethical standard unless the aging process could be prevented. But neither Rand nor Merrill derives immortalism from this argument.

Second, if Rand, as interpreted by Merrill, really has turned ethics into a "matter of engineering," then the burden in decision-making is shifted from ethics onto epistemology – which by Merrill's own admission is the weak link in Objectivism! The thought-experiment I quoted above is perforce an ethical problem which Objectivism cannot obviously solve.

Fortunately Merrill provides himself an escape from the first dilemma by presenting life not as one state of a binary condition (the other state being death), but rather as a continuum of value-seeking. In a passage that may express ideas familiar to many cryonicists, Merrill writes:

> If life is defined in terms of an organism's exhibition of goal-directed behavior then we must visualize the possibility that it can exist on a multitude of levels. On what we might call the "hamburger" level, cellular behavior is very primitive, consisting of a small set of rather simple tropisms. The "warm body" level, in which all or at least some organs are functioning, represents a higher level of complexity. When the organism – a human being, in the case we are concerned with – is able to perceive and to act, then the range of goals accessible to him expands enormously, and it is only at this level that we would regard him as "completely alive." And yet, need we stop here? If our subject is more alert, more intelligent, more healthy, more strong, is he not more able to select goals and pursue them, and is he therefore not more alive yet?

Merrill does not delimit the upper range of this continuum, but the implication is that it is open-ended. Nor does he draw the obvious inference, so I will: The Objectivist ethics pushes us in the direction of increasing the value of our lives without limit, which implies transforming ourselves into immortal superhumans. Merrill himself acknowledges that the Objectivist virtue of pride requires the Objectivist to "make a commitment to self-education and self-improvement, to the constant expansion of his competence to deal with reality" (thereby approaching the Extropian principles of Self-Transformation and Boundless Expansion). The irony of Merrill's analysis is that he fails to see that an unaging transhuman would meet the Objectivist standard of ethical excellence better than an ordinary human.

Beyond the Objectivist ethics lies its practical application in politics, described in Chapter 7. Merrill analyzes Rand's philosophical differences with both conservatism and libertarianism. Her critique of conservatism is on the mark, for conservatives are only half-way committed to the cause of freedom; as soon as they assume "power," they begin to compromise their principles for the sake of popularity. Despite the fact that the Republican Party has had its way with the Executive Branch of the U.S. Government for twelve years, it has not stopped the progress towards socialism in this country.

On the other hand, Rand's critique of libertarianism is problematic, for as Merrill complains, she never explained her view of the Objectivist Just State. Part of the problem is that "libertarianism" is a catch-all term for a range of philosophies united around the assumption that the State is inherently evil. As a consequence, the only way the adherents of these otherwise disparate philosophies can work together is under the banner of moral tolerance.

As Merrill sees it, libertarian moral tolerance contributes to the dispute about the nature of the social contract. The anarcho-capitalist school of libertarianism, which "defends the indefensible," argues that the Lockean view of the social contract — where the individual gives his "free" consent to be governed by the State —is really a sham, for the State controlling any geographic area is a monopoly and is able to dictate its terms by force. Hence true freedom can be found only in a competitive market for the services that the State traditionally offers.

Rand's view, on the other hand, is that (a) political freedom needs to be based on an objective standard of morality, and (b) "the Objectivist Just State is to merit its authority because it implements objective, knowable moral principles." Because of her assumption that there can be no conflict of interests among rational beings, Rand therefore seems to argue that one's entry into an ethical social contract is "pure profit." As Merrill writes, "In giving up the chance to live as a predator, the individual is losing nothing."

There are serious difficulties with the Randian view, however, because humans make decisions based mostly on emotions and naive or neurologically hardwired heuristic procedures, and rarely based on explicit epistemological principles — and we have just seen a major weakness in Rand's epistemology. For evolutionary reasons humans currently cannot sustain lifelong, consistent rationality. It will take technological self-transformation of the human brain, along with progress in epistemology, before any hypothetical society of rational individuals becomes possible. (In which case one might speak of a "society of rational transhumans.") Under the limitations of the human condition, a society based on anarcho-capitalism might be an improvement over ones based on statism, but such a society would still have problems caused by the discoordination of the human brain. Rand's ignorance of the modular-mind perspective leaves her philosophy vulnerable to attack as a form of rationalism rather than as a systematization of rationality.

Where Merrill and Rand are both right, however, is in their emphasis on objective morality as an antidote to the growth of the State. Merrill argues that "libertarianism has failed by its success" in eroding social controls over shiftless behavior. Its doctrines of ethical subjectivism and "doing one's own thing" have produced more anomie than anarcho-capitalism, with the result that the law-abiding people are calling on the State to protect their families from an ever-worsening breakdown in social order. "Moral tolerance" has reached bankruptcy when self-proclaimed "community leaders" demand amnesty towards thugs arrested for arson, looting, and beating up innocent bystanders on live television.

Only a people who can maintain a sense of "doing the right thing," as Albert Jay Nock phrased it, can live in a sustainably free society. Because of the collapse of morality, "the defenders of the indefensible face the political backlash," as suggested by the recent Republican National Convention. This reaction would not be called for if people, like the inhabitants of Galt's Gulch, "did the right thing" in the absence of the State's coercive supervision.

Fortunately Merrill ends his book on a positive note. He calls for the re-creation of the Objectivist social network that existed before the abolition of NBI, and recommends that Objectivists study new areas of knowledge, such as sociobiology and chaos theory, to add "smart weapons" to their intellectual ammunition: "Technology has changed, the economy has changed, society has changed — and our vision of the organization of the free society must change too." And: "Half the genius of Ayn Rand was that she saw what everybody saw, and said what nobody dared to say. We need once again to become intellectual leaders, to have the courage to approach the cutting edge of new thought." (Merrill seems to be looking once again for Self-Transformation and Boundless Expansion.)

Along with networking, education, and setting good examples, the Objectivists' most powerful tool is Rand's concept of "the sanction of the victim." Evil survives by drawing its strength from the good, so withholding the sanction is one of the keys to victory in the long term. (Merrill's example of a sanction of the victim: "When businesses give money to universities and foundations that attack capitalism, ... the moral force of their example far outweighs the financial assistance. Whenever and however we may choose to fight, this kind of issue is the where.") However, Objectivist leaders ought not to "excommunicate" freethinking neo-Randians who disagree on peripheral issues, for Rand's, and now Peikoff's, habit of condemning dissenting Objectivists has caused more harm than good. Merrill then expresses his hope that Rand will be remembered by history as one of the greatest thinkers of our century, with our views of the just society and the function of philosophy changed in her favor.

Clearly the writings of George H. Smith and Ronald E. Merrill represent progress in upgrading the Objectivist worldview into something I call "Objectivism 2.0." Merrill, especially, is a "trans-Randian" groping towards something like Extropianism. His kind of boundlessly expansive Objectivist thinking needs to be nurtured and encouraged to counter the dogmatism of the Peikoff school. Both of the books I have reviewed are worth adding to one's Extropian library, but Merrill's is the better value of the two.

Nanosystems: Molecular Machinery, Manufacturing, and Computation

By K. Eric Drexler

New York: Wiley-Interscience, 1992; 556 pp. Hardcover $42.95, ISBN 0-471-57547-XPaperback $22.95, ISBN 0-471-57518-6

Reviewed by J. Storrs Hall

In 1610, Galileo published a small book entitled *Siderius Nuncius* which set the world on its ear. It was, in many respects, the keynote publication of the 17th century. In it he described what happened when he took an existing tool, the telescope, and turned it on the realm of the heavens. He had discovered mountains on the moon, and moons around Jupiter. The old conceptions of the universe were, at that point, doomed, and the following century would see a complete restructuring of our basic understandings of nature, and kick the Rennaisance into high gear.

In *Nanosystems*, Drexler takes the tool of mechanical engineering and turns it on the realm of the molecular. *Nanosystems*, in my humble opinion, is destined to be the keynote publication of the 21st century. There will not be a person alive in 2100 who is completely unaffected by the consequences of the ideas presented here.

Suppose you had a mechanical manipulator so small, and so precise, that it could handle individual molecules, maybe even atoms? You could build (small) objects with a precision that would allow you to specify in your design where each individual atom was to be, exactly which atoms would be covalently bonded to which other atoms, and so forth. If indeed you could build objects with this degree of precision, you could design and build some rather incredible things – like the mechanical manipulator we assumed in the first place.

If we could bootstrap ourselves into such a technology, we could gain essentially atomic-level control over the structure of matter for a multitude of purposes. Such a technology is called nanotechnology or, to distinguish it from more conventional approaches to nanometer-scale operations, molecular nanotechnology.

Drexler's previous books, *Engines of Creation* and *Unbounding the Future*, gave a glimpse of what molecular nanotechnology might mean. Indeed *"Engines"* was one of the major factors behind the flourishing of the cryonics movement in the mid-80's. However, these books were written for the popular audience. *Nanosystems* is written for the technical audience.

Even so, much of *Nanosystems* is introductory or explanatory compared to the average technical book. The reason for this is clear: most technical books are written for the specialist in a particular field, and there are virtually no specialists in this one.

The burden of *Nanosystems* is simple in overall concept: it is a proof that molecular nanotechnology can work. As such it has two major parts.

First Drexler develops and justifies the theoretical tools he needs to analyze nanomechanical devices. This involves a unification of principles from physics, chemistry, and engineering. He explores the various levels of abstraction at which physical laws are used, from quantum mechanics to the continuum models of engineering which ignore the molecular nature of matter entirely. Of particular interest are the empirical molecular mechanics models, which seem to be the appropriate tradeoff between accuracy and efficiency for analyzing nanomechanical designs.

Second, he exhibits actual designs, with analyses, sufficient to make a strong case that a full-fledged, self-reproducing, molecular technology could be built from the devices presented and others like them. We have axles and bearings, gears and cams, pumps, motors, generators, and computers. There are chapters on the internal processes of, and the overall structure of, molecular factories. There is a detailed design for a robot arm 100 nanometers long.

There is a point of some importance that is generally ignored in higher-level discussions of nanotechnology. It forms the bridge between the first and second sections. If you had the manipulator arm with the ability to put each atom where you wanted it, would that really give you the ability to build objects with them? Surely the reactive atom you were trying to add to your workpiece would bond more quickly to the manipulator itself?

Of course, adding one atom at a time,

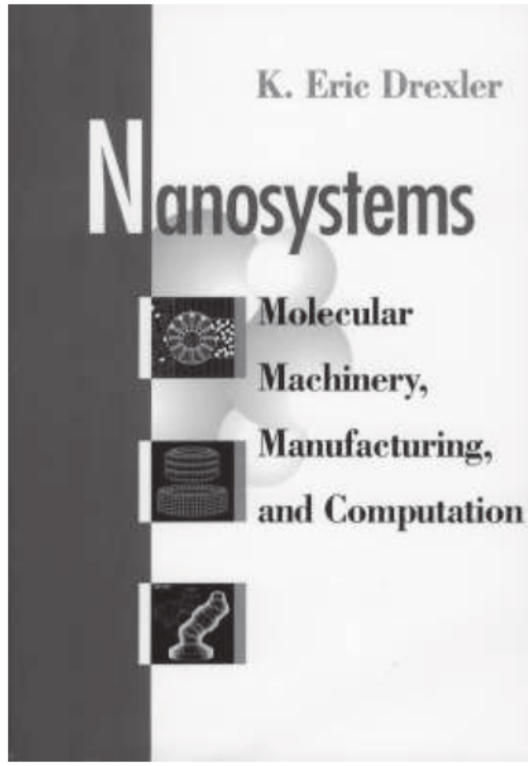
like laying bricks, is not what is actually envisioned in the synthesis operations. What must actually be done is quite a bit more complex and looks a lot more like chemistry. The explanation of this "mechanosynthesis" is the "missing link" in the common understanding of nanotechnology; but it's not missing here. It's chapter 8.

Anyone with experience in the construction of macroscopic objects is aware that the process typically involves a plethora of tools and clamps and jigs and molds and scaffolding. So too in molecular construction: we might have a complex molecule that will undergo a chemical reaction if held to a certain kind of spot on a surface, adding one or two atoms in a certain configuration. We might build up the structure we want by holding a succession of the "tool" molecules to the workpiece in a careful pattern, recycling the depeleted byproduct molecules to be recharged by conventional chemical means.

One example of molecular scaffolding is the relatively recent ability to grow diamond. This depends on the presence of hydrogen, without which the surface of the diamond is unstable and graphite is formed instead. Clearly nanomechanical synthesis of diamondoid structures would use the same kind of scaffolding!

The final chapter is not part of the logical development of the "proof of nanotechnology" but is just as important: the question of how we get there from here. There is a host of pathways. Drexler sketches a few of them here; but it is the very multiplicity of options that makes the ultimate goal relatively certain, and thus the book as a whole so important.

Nanosystems is intended to be accessible to the interested technical reader from any field, providing the person is willing to do enough brainwork to assimilate the concepts. If you've read and largely understood Asimov's *Intelligent Man's Guide to Science*, you'll find *Nanosystems* comprehensible; however, the more work you put into it, the more you'll be rewarded. I spent half a year working out, in my own specialty, some of the implications from just a few pages in the nanocomputers chapter (from a pre-publication draft).



In the years following 1610, *Siderius Nuncius* was highly sought after. People adopted Galileo's methods, and new discoveries came thick and fast: Spots on the sun; phases of Venus; rings around Saturn.

With the publication of *Nanosystems*, our old bulk technologies are doomed. The following century should see a complete restructuring, not only of manufacturing, but of our basic relationship to nature. A new Rennaisance is the least we should expect.

Genius – The Life and Science of Richard Feynman

by James Gleick

Published by Pantheon Books, 1992, a division of Random House, Inc., New York
ISBN: 0-679-40836-3

Reviewed by Harry Shapiro

No scientist has ever captured my imagination more than Richard Feynman; Certainly I am not alone. James Gleick, the author of *Chaos*, has tried to provide a more detailed, accurate and scholarly view of Richard Feynman. Having previously read, *Surely you're joking Mr. Feynman*, and *What do you care what other people think?* [1] I thought I knew him already. Gleick has clearly tried to find and present the Richard Feynman that isn't revealed by the humorous volumes mentioned above. "He penetrates beyond the gleeful showman depicted in Feynman's own memoirs and reveals a darker Feynman: his ambition, his periods of despair and uncertainly..." [2]

I have made a practice in reviewing books for *Extropy* to focus not only on the book but how it directly relates to Extropian philosophy. I will continue this practice here. I doubt that any Extropian minded individual has any doubt about how the science of Richard Feynman relates to the Extropian view. Feynman is regarded as the "intellectual father" of nanotechnology because of his famous speech arguing that "there's plenty of room at the bottom. [3]" I was delighted to learn about other areas in which he seems to me to directly reveal an Extropian outlook. I will discuss this below. Overall I was both satisfied and greatly disappointed with this book.

Gleick clearly was trying to present the whole man; he succeeds in many ways. He reveals Richard Feynman as an explorer of self, and nature. Many details are provided about the major and key efforts that Feynman made when working on the Manhattan Project – details that Feynman left out of his own books. Neither are personal details left out, including facts about his sexual relationships, and use of psychoactive chemicals (marijuana and LSD [4]). At the same time, other details seem left completely out. In Feynman's books, for example, he spends much time talking about his own paintings. This is barely mentioned by Gleick. The lack of details about his painting seems surprising because Gleick does expend much effort writing about Feynman's ability to visualize. I would have enjoyed a critical look at the paintings as much as the looks Gleick provides of Feynman's other "art work," "the Feynman Diagrams."

Some of the disappointment I found in the book relates directly to how Gleick presented Feynman's various scientific discoveries. It wasn't enough to talk about each topic (from particles and waves to DNA). Some detail of previous discoveries was clearly called for. Gleick not only provided these details but what amounted to an oral history of modern physics, and, almost, a primer in modern physics. I am not a physicist, though I have taken courses in it. I found Gleick's long, often several page descriptions, background details, and philosophical overviews to either tell me what I already knew or didn't really tell me enough. I suspect, that except for a select group of readers these parts of the book will be seen as rather boring, though Gleick was true to the books sub-title – "The ... Science of Richard Feynman."

The most interesting parts of the book were for me, as indicated above, those details that seem to scream out: "Richard Feynman was an Extropian!" This included a rejection of religion, and a seemingly libertarian view of economics (page 397). I will present a few of these below.

One of the famous, or perhaps infamous, topics on the Extropian Mailing list [5] is the uploading of human consciousness into computer-like devices, and related topics such as the nature of consciousness. On page 124 Gleick details a cross-examination of philosopher Adolph Gruenbaum by Feynman who was identified as "Mr. X."

Gruenbaum: I want to say that there is a difference between a conscious thing and an unconscious thing.

Mr. X: What is the difference?

Gruenbaum: Well ... I would not be worried if a computer is unemployed,... I would worry about the sorrows which that human being experiences in virtue of conceptualized self-awareness.

Mr. X: Are dogs conscious?

Gruenbaum: Well, yes. It is going to be a question of degree. But I wonder whether they have conceptualized self-awareness.

Mr. X: Are cockroaches conscious?

Gruenbaum: Well, I don't know about the nervous system of the cockroach.

Mr. X: Well, they don't suffer from unemployment.

Gleick writes, "It seemed to Feynman that a robust conception of "now" ought not to depend on murky notions of mentalism. The minds of humans are manifestations of physical law, too, he pointed out. Whatever hidden brain machinery created Gruenbaum's coming into being must have to do with a correlation between events in two regions of space – the one inside the cranium and the other elsewhere 'on the space-time diagram.' In theory one should be able to create a feeling of nowness in a sufficiently elaborate machine, said Mr. X."

Another topic that appeared on the Extropian list is the issue of how small computers could actually be made. Someone wondered if they could be reduced below the atomic level. On page 435 Gleick writes, "He joined two Caltech authorities on computation, John Hopfield and Carver Mead, in constructing a course on issues from brain analogues and pattern recognition to error correction and uncomputability. For several summers he worked with the founders of Thinking Machines Corporation, near MIT, creating a radical approach to parallel processing; he served as a high-class technician, applying differential equations to circuit diagrams... And he began to produce maverick research at the intersection of computing and physics: on how small computers could be; on entropy and the uncertainty principle in computing; on simulating quantum physics and probabilistic behavior; and on the possibility of building a quantum-mechanical computer, with packets of spin waves roaming ballistically back and forth through the logic gates."

Of course computers were not new to Feynman. He had worked with the primitive card-driven mechanical calculators at Los Alamos. On page 201 Gleick writes, "His computing team had put everything aside to concentrate on one final problem: the likely energy of the device to be exploded a few weeks hence at Alamogordo in the first and only trial of the atomic bomb.... He had invented a system for sending three problems through the machine simultaneously. In the annals of computing this was an ancestor to what would later be called parallel processing or pipelining. He made sure that the component operations of an ongoing computation were standardized, so that they could be used with only slight variations in different computations... He also invented an efficient technique for correcting errors without halting a run."

There are many other example to choose from. I have chosen these because they seem to stick out in my mind. Examples of pushing technology to the edge of understanding, examples of innovation and the optimism to forge ahead in the face of adversity. Adversity in the nature of our universe – Feynman writes, "If it turns out there is a simple ultimate law which explains everything, so be it – that would be very nice to discover. If it turns out it's like an onion with millions of layers ... then that the way it is."[6] Also adversity on more a more personal level – Feynman's first wife Arline was dying throughout his time at Los Alamos – he had the strength and courage to be with her emotionally and physically almost every weekend, while having the concentration to continue his work on "the bomb." He was dying of cancer during his work on the independent commission investigating the Challenger explosion. Again adversity was met and overcome, while Feynman was once again able to capture the attention of the nation.

If there is anything non-Extropian about him it is that he accepted his own death. However, he didn't retreat into the mythos of religion: "I can live with doubt and uncertainty and not knowing... I don't feel frightened by not knowing things, by being lost in a universe without any purpose, which is the way it really is as far as I can tell. It doesn't frighten me." [7]

In conclusion, I will say that for anyone who wants to have a deeper insight into Richard Feynman, *Genius*, is required reading. However the book does not stand alone. For readers who have a detailed knowledge of physics, or for those who don't want one, the book may very well prove disappointing. If you are looking to introduce someone to both Feynman and the science he espoused, then the book comes highly recommended. I found the book hard to put down, but did on occasion, yet I am glad I have read it. I would urge Mr. Gleick to write more about science, using people as backdrops rather than using a biography to teach science.

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[1] Written by Ralph Leighton as told by Richard Feynman.

[2] From the book jacket to *Genius*

[3] A speech presented at the 1959 Annual meeting of the American Physical Society and later reprinted in Caltech's *Engineering and Science* magazine and *Popular Science Monthly*. (See *Genius* pages 17, 354-355)

[4] His use of LSD came as a revelation to me. I thought I remembered reading that he didn't use it for fear of disturbing his thought processes.

[5] You can join the Extropians list by sending e-mail to extropians-request@gnu.ai.mit.edu. Prepare to be beseiged by many messages per day.

[6] Page 432

[7] Page 438

CLASSIFIED ADS

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Extropy #10 was produced on a Gateway 486-50DX2 PC with 8Mb of RAM and a 200Mb hard disk, running Windows 3.1, and using Aldus Pagemaker 4.0, WinWord 2.0, and Aldus Freehand 3.1.

Print run this issue: 2500

Printed by Hollywood Stationery & Printing, Los Angeles, California.