Computational Models from A to Z

A version of these thoughts was presented as the keynote lecture at Swarmfest 1999 held at the Anderson Business School at UCLA on March 26, 1999. Any part of this piece that is interpreted as humorous should be accredited variously to Jenna Bednar, Ken Kolman, John Miller, Troy Tassier, Leigh Tesfatsion, or Nick Fried. Their comments helped me to emend an earlier, drier version of this work that also had hints of raspberries and an oaky aftertaste, which I am afraid have been lost.

The growing use of computational models of social, physical, and biological systems raises many questions and concerns. Platforms such as SWARM enable researchers to construct detailed, robust computational models. The availability of SWARM-like platforms will speed the pace of the computational revolution and open new areas of research. In this brief, tongue-in-cheek commentary, I discuss 26 topics pertaining to these computational models. Unbelievably, each of the 26 subject headings begins with a different letter! Given this fortuitous fact, I have chosen to arrange the topics alphabetically. Though containing bits of levity, this article should be read seriously both as a social scientist's commentary on a nascent field and as a guide to future research.

Applications: Michael Cohen has said that complexity research must move beyond the “festival of bad metaphors.” With that in mind, I’ll begin with a bad metaphor. During a recent trip across the country, I stopped in South Dakota where I saw legions of tourists filming Mount Rushmore. If videotaping a fixed object strikes you as odd (maybe they hoped to catch Washington’s nose falling off on tape), consider the opposite: analyzing the flow of the Mississippi from a single aerial photo. (Incidentally, see “Rising Tide” by John Barry [1] for a detailed description of the madness that is the Mississippi.) In other words, the adage “don’t saw a board with a hammer, and don’t pound in a nail with a saw” also applies to scientific inquiry.

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Computational models enable the study of complex, dynamic worlds because they themselves are dynamic. To understand complex, dynamic processes, it makes sense to construct dynamic models, "buff said. It follows then that computational models should prove their worth in analyzing complex situations: environments with agents whose actions and payoffs are interdependent.

role in the abilities of a political leader to spur nationalistic passions. Simulation methods will not solve these problems, but they can help us to understand how such systems behave and—with all due respect to Schelling [2]—how the micro-level behavior maps to aggregate phenomena. Finally, let me conclude by noting that I am not against equilibrium models and representations of realities. I like paintings. I even enjoy some sculptures (especially those with people, horses, and dogs). As for those El.ASCII maps that we watched in seventh grade, were these the first discrete time step simulation models? I'll leave that question to historians of science.

Behavior: Murray Gell-Mann [3] has been attributed with saying, "Imagine how hard physics would be if electrons could think." He's right about that (and many other things). It would be difficult. The distinction between physical entities following laws (like that one that applies to gravity) and responding to stimuli versus intelligent agents that alter their behavior is important to keep in mind when constructing social science models. We know that the atoms in the fenders of two cars about to crash do not alter their behavior (or at least we think we know that). The drivers of the cars, on the other hand, typically do react. What I am saying is that writing down a fixed behavior and saying "this is what carbon atoms do" may be fine. It may even be acceptable to write down a rule of thumb and say "this is what bees do" (among the cogniscottle this is known as bee-havior) provided that the behavior is stable evolutionarily. But, one should never say "this simple rule is what people do" (even if they did learn it in kindergarten) unless those people are coming close to optimizing their information. Why? Because people learn. People simulate the world by creating models, whether mathematical or more abstract. People either continually (economists think this) or occasionally (psychologists think this) try to think of ways to improve their actions [4]. This does not imply that you need to assume optimal behavior, quite the contrary. But your agents do need to have the potential to improve their thinking.

Comprehensive: In his award-winning book Guns, Germs, and Steel, Jared Diamond [5] puts forth a theory as to why the fertile crescent emerged. He claims that a combination of factors, the size of seeds, the presence of animals capable of domestication, and the east-west orientation of the continent led to the growth of human society in the crescent, as opposed to, say, in Finland. Diamond's extended analysis describes how the domestication of animals led to improved human immune systems (shockers: cows carry diseases!). This increased immunity proved to be at least as valuable as steel and guns in conquering hunter-gatherer societies. After reading Diamond's book (or almost anything by James Burke in Scientific American) you come away with this feeling that partial analysis has severe limits. Could money supply and disease be related? Two words: Black Death. For another recent example consider the Sugarscape model of Epstein and Axtell [6]. Its comprehensive approach to modeling combines trade, culture, and disease. Their model should not be seen as a culmination, but as an opening. Everybody talks about interdisciplinary work; computational models allow you to do it (see Axelrod [7]). But, as many computationalists will tell you, you cannot include everything in one model. De dubious if someone has a model that explains both the panda's thumb and the chia pet.

Decentralization: Computational models, like the physical and social worlds, do not have an active central planner [8]. (They do have an omniscient overseer, who reboots if things go awry—and so may the real world!) In my opinion, the big issue in decentralization is the emergence (see E) of coordinated behavior in the absence of a coordinator. Melanie Mitchell, Peter Hraber, and Jim Crutchfield [9] at the Santa Fe Institute have constructed a series of models in which agents with local knowledge and communication structures can coordinate their behavior. They don't only obtain this result in a computational model, but they also provide a proof as to how and why the coordination occurs. We too often fail to be amazed by the order in markets, forests, lakes, and train station lobbies. I'll stop here before I become some sort of Walt Whitman—Thomas Schelling intellectual love child.

Emergence: My first "buzz word" of complexity: Emergent speaking, emergence refers to a computation or phenomenon at the macro-level that was not hard-coded at the micro-level, such as when a market computes the price at which supply equals demand even though no one is trying to compute the market price. Stephanie Forrest has written extensively and clearly on what is meant by emergence, and so has some guy named Holland [10]. (He even has a book by that name, but he has never stated whether he wrote it or if it just appeared one day on his computer.) What's the big deal about emergence? The unexplainable. When we say something emerges what we mean is
that you never would have guessed the result from looking at the parts. Make pastry dough in your Cuisinart sometime. Watch how in the space of one breath, a jumble of swirling flakes transforms into a ball that floats above the spinning blade. Imagine placing a bunch of chemicals in a blender, pushing the puree button, and seeing the thrashing liquids combine to form a froth. I’m being rather unscientific in my discussion of emergence. Is it just the unexplainable? And if it’s happening at a different level, doesn’t it have to be unexplainable? If you want to think more deeply about what has often been a fuzzy concept, read Joshua Epstein’s [1] thoughtful analysis.

Friends: John Miller (a friend) and I often assign the following problem: Construct a model to simulate a standing ovation in a theater [12]. When we ask economics graduate students to perform this exercise, their models differ from those of others (dare I say “normal people”) in one important respect. The budding economists assume that each agent (that’s what economists call people) is alone. Other people, even Caltech undergraduates, tend to assume that people go to the theater with friends and that their friends’ behaviors have a strong influence. Returning to the letter A, we see that in many of these examples, friends matter. Hmm. . . . By keeping track of friendships, we can perhaps better understand social life, whether it be social networks in Florence hundreds of years ago [13], transmission of diseases in the modern day, or in simulated games taking place within the safe confines of our computers [14]. We can also better track the flow of information. Most social science models make aggregate level assumptions about information: “Prior is normally distributed. Blah blah blah.” A great deal of information flows through networks of friends. These standard distributional assumptions may be inaccurate and, in some cases, lead to incorrect conclusions.

Distance can be measured in miles. Notice though that the degree of separation between people defines a geography on friends. Multiple distances create nontrivial relationships. A friend told me about seeing a car in Tel Aviv with four people, each talking on a separate cell phone.

Location theory used to be a big part of economics. Paul Krugman has recently advocated that economists pay more attention to geography. His models provide some insights into how economic activity organizes in space, but he admits that many big questions remain unanswered. (For those non-social scientists still reading:) A natural science question worth studying computationally is how animals organize themselves in space, whether it be on the African savannah or in response to encroaching urbanity. Just a few weeks ago a coyote was trapped under a cab in front of the Chicago Art Institute. He came for the rats. He stayed for the Van Gogh.

History: It matters. Whether it matters as much as Gould and Lewontin would have us believe or whether some arrangements were inevitable remain open, interesting questions, but regardless, it matters, even in the development of the agents. You can think of an agent as just a collection of preferences, abilities, and information, but you can also include the history of events that the agent has experienced. That history will play a role in how the agent chooses among its skills in a particular situation.

Imitation: Copying on tests is cheating. Copying in life is learning. Successful people, firms, and organizations likely possess replicable behaviors that if copied would help others to be successful too. This logic supports an entire industry of management consultants. “Come on, let’s do it the GE way.” And, it’s partially correct; even Hayek recognized this [15]. Imitation also underpins fads. In a society where people struggle to survive, fads probably matter little. If I eat a yam and my best friend also eats a yam, it may be because yams are the only thing we have to eat. In modern society, with our abundance of commodities (and our culturally induced in-securities) enormous amounts of money are spent on wants, as opposed to needs [16]. If we want what others want, we can tip into many different equilibria. We could all wear baggy jeans. We could all get tattoos. Sam Bowles refers to these as “egg carton” equilibria. Drop a marble into an egg carton, it could land in any of twelve places.

Imitation occurs for many reasons: network externalities (the QWERTY keyboard, MACs vs IBM, Beta vs VHS), informational cascades (all the cool people are using LaTeX, it must be easy), economic spillovers (if more people commit crimes, then the costs of committing a crime fall), and pure peer effects (I want to be like Mike). It even occurs in science [17]. This imitation can lead to big winners and big losers in the economy. In political settings, it can lead to the election of tyrants (or even wrestlers). Imitation sounds like a fun, easy thing to model, but it leads to tricky dynamics. In some cases, imitation for informational reasons leads to ambivalence. If everyone imitates, then the information from other people is worthless, so I should follow my own lights. If no one else imitates, then I might benefit by imitating the majority. Therefore, the level of imitation in society might evolve up to the point where the benefits of imitation fall to zero. Thus, imitation will evolve to a level where it is no good, sort of like supermarket tomatoes.

Jazz: In jazz, given a basic musical structure, the players adapt in response to the actions of the other players, creating an emergent sound that cannot be understood as the mere sum of its parts. The science of complex systems awaits for its Miles Davis, spinning out profoundly emergent sounds.

Knowledge: In a complex system, knowledge exists at several levels. There is the knowledge of each agent and the knowledge of the system. Here, I refer you to the Hutchins book Cognition in the Wild. He describes the piloting of a large ship into a harbor under an electrical shutdown. No one person has the knowledge of how to steer a massive ship. That knowledge is distributed across many agents, some controlling
rudders, some adjusting engines, and some managing crew. Come on. Do you really think that Bill Gates knows how to run Microsoft? Or that he does it optimally? Knowledge even exists at many levels within an individual. Though I am able to ride a bicycle, I really don't know how to ride a bike (though, I'm told if I learn it, I'll never forget). I cannot tell every synapse when to fire and every muscle how to move. The knowledge is tacit.

Levels: Quarks, atoms, cells, organs, people, families, casts, nationalities... I was once told that in constructing good models, you have to learn when to use a microscope and when to take off your glasses and let things be fuzzy. In simulation models, we ignore that advice to some extent and allow our models to proceed on many levels simultaneously. Artificial agents may contain genetic material that determines the range of their behavioral repertoire. They may also belong to an identifiable group. Genetic, individual, and group selection may occur simultaneously. To see how these may be at odds, let me give a simple example that borrows ideas from Joe Harrington [19], Lars-Erik Cederman, Samuel Bowles, and Herb Gintis. Imagine a world composed of thousands of islands. On each island people can either be thieves or farmers. Imagine further that there are three types of genes, one that makes you a thief, one that makes you a farmer, and one that makes you an opportunist—you do what is best in your environment, but at a lower level of productivity. You might expect to find some thieves and some farmers on each island. However, suppose that these islands can wage war on one another and that the island with the most resources usually wins. This is much like the board game Risk. An island that happened to have a population of all farmers would do well in wars against other islands. But on that island a mutation to being a thief might be beneficial. Depending on the model, you might see either thieves, farmers, or opportunists survive in the long run. It all depends on how fast the selection occurs and on what levels.

Mental Models: People have mental models of the world that they use to guide their behavior. Fortunately, we don't all have the same mental model. This diversity of problem-solving approaches enables collections of intelligent, bounded agents to locate solutions to difficult problems. Lu Hong and I have constructed models where agents have perspectives (problem encodings) and heuristics (rules of thumb, tricks) [20]. The simplest examples of diverse perspectives are the Cartesian and polar coordinate systems. Each encodes the same reality—a geometric point or object. Some objects lend themselves to analysis more easily one than the other. If I want to find the value of an integral over the surface of a sphere, I'll use polar coordinates. The right encoding on a specific problem can appear to be a touch of genius. I once read a Freudian biography of Newton. Newton's father died when Newton was young, and Newton's mother subsequently remarried. Isaac was shuffled off to relatives, and his mother lived approximately 30 kilometers from him; later she moved to another house, again, approximately 30 kilometers away. Like all scientists (at least according to their Freudian biographers), Newton was strongly attracted to his mother. Thus, he may have been blessed with just the right perspective: to think of things that are strongly attracted as orbiting at a fixed distance. Heuristics also differ across individuals. The development of a new heuristic, the calculus or linear programming, for instance, can lead to improvements on many problems in a short period of time. Innovation, which I have already discussed, often occurs in the space of heuristics.

Novelty (perpetual): Each day is different. Even in the movie by that name, no two Groundhog Days were identical. Bill Murray's adapting behavior changed the reactions of the people around him until eventually he got the girl. Admittedly, there are some regularities. Our ability to learn from one day to the next requires it. But our adaptive responses, combined with exogenous shocks, create a world of which a portion is perpetually novel. It follows that no accurate model of the world can have teleological agents. People do not always know where they are headed. In some cases, there may be a tendency toward stable points (equilibria), but even then, those equilibria may keep moving. In other cases, novelty reigns. Long may it. Now, if we could only explain it.

Optimality: Evolution need not lead to optimality (just look at your relatives). It can get stuck in local optima. If we are optimal, why do we eat and breathe through the same hole (and occasionally choke). In social, political, and economic settings, the decisions that people make need not be optimal either. And, no matter how many social scientists assume optimality in their models, they won't make it any tiler. The assumption is incorrect. But, it is not silly. Optimality is a nice benchmark and leads to testable predictions. As Emerson might have said, "To model is to be unrealistic." People like facts. So here is a good one. In a episode from the Batman television series, The Caped Crusaders are about to be catalyzed to their deaths. Batmanstrains to reach his Batwatch to program the Batmobile to speed to their ultimate location and provide a cushy landing. In determining their landing point, Batman becomes computationally constrained and turns to his sideskew and asks "Quick Robin, what's the cube-root of pi?" Robin stalls, and then Batman says "Never mind. I figured it out myself." (Quick—what's the cure for cancer?) For the record, the cube root of pi is approximately 1.465, and Batman and Robin did land in the Batmobile—but in the wrong seats.
Pitfalls: Computational models have many problems. Notice that I did not use the word pannoces for the letter P. Even emergence can be a problem. The agents tend to do what we ask them to do. If we ask them to walk through a door, they'll walk through it. They also will adapt novel solutions to problems that we never would have imagined. Karl Sims' model evolved creatures that moved. He found after one epoch that tall speices that just fell over had evolved. Given his measure of fitness, horizontal displacement of center of mass, this was a fit species. Rumor also has it that Karl's model moved agents who spanked themselves in the rear to get greater propulsion. Upon seeing this, Karl realized that he had forgotten to include a constraint on conservation of momentum. (An alternative interpretation is that he had explained the extraordinary performance of Catholic elementary schools.) Since this piece is meant to encourage you to experiment and play with computational models, I'll stop with the negatives and just give some friendly advice: DO A REALITY CHECK!

Quivers: Almost all computational models include randomness at some level. (Okay, in reality, deterministic random number generators create the sequences of numbers, but from the agents' standpoint it's randomness.) This randomness can enter in the initial conditions, in the agent's behavior, in timing decisions, and in allocating resources. In a good computational model, the random effects will add richness but will not drive the results. The patterns should not depend on specific random number seeds, so careful researchers use multiple random number generators. Results also should be run in other platforms. Although Santa Fe's SWARM is an impressive general purpose simulator, as a community we need to encourage swarms of SWARMS. Results not robust to a choice of platform are not results.

Rudolph: According to legend, although initially not invited to participate in reindeer games, Rudolph became the most famous reindeer of them all. Think of Rudolph as an unwanted resource who filled a niche. But Rudolph was not the only possible solution. "Freddy-The-Fog-Horn-Nosed-Reindeer" may have lived during a time with no bad weather, and so he never achieved the fame or fortune of Rudolph. What I am trying to say (with the benefit of hindsight?) is that while species evolve to fill niches, an equally powerful force is the ability of agents to use endowments creatively to achieve ends. The laser was originally thought to have few applications. In computational models, language may be included to introduce communication, but agents may use it to create secret handshakes to discriminate against one another.

Selection: I have already hinted at some of the many issues associated with selection. Cultural and biological selection differ. For instance, the former is Lamarckian. Selection can be too severe, cutting off exploration at the expense of exploitation. Selection can be overused; evolving solutions that may be fixed parts of the environment. I have even heard a story about the evolution of gravity. Initially, some apples flew upward when leaving the tree, some went flying parallel to the ground, and still others fell, earth-bound. Only the last type reproduced. More seriously, selection does occur in the marketplace, but not as much as you might think. If I own an asset and do not use it optimally, then someone may well come and buy that asset from me at a price I cannot refuse. But individuals can make incorrect, biased decisions and not feel much evolutionary pressure. For example, the other day, I was in the grocery store, and the woman in front of me was about to buy the wrong-sized package of a product (the smaller size was on sale for less per ounce). I informed her of this, and she thanked me. Little did she know that I was an economist I would have had to kill her had she made the wrong choice (lest she reproduce and more of her kind undermine our efficient marketplace).

Timing: Early simulation models such as the Game of Life rely on simultaneous events. Bernardo Huberman has described this as a German marching band model. Huberman and Glance [21] show that if updating actions are asynchronous, then the game of life becomes the game of death. No gliders. No figure eights. Just static. I found this work so interesting that I wrote a response [22]. I too allowed for asynchronous timing, but I made my model incentive-based. Agents who had the most to gain by updating were the first to change their behavior. Depending on how you assign utilities, this assumption can resuscitate the Game of Life. Interesting patterns re-emerge, though I have yet to locate any gliders. A second issue related to timing concerns scale. Here is a little bit of doggerel to remind you that although religions, technologies, and diseases all flow through societies, they do so at different rates.

A young Catholic girl named Annie was suffering from the flu. She ran into old Bob Frankel, hale and hearty, but a Jew. They shared some food and drank some ale and danced the night away. Come morning Bob felt funny, but why he couldn’t say. His head! His chest! He was sick all right, but he was Catholic too!!

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COMPLEXITY
Universality: You can draw a continuum on one end of which you have the word "unicorn" and on the other you have the word "universal." If you prove a mathematical theorem, then you have a universal result. Provided that your math is correct, whenever your assumptions hold, so will your result. With computational models, this is not true. At best, we can say that with some probability a finding is true. Any one instance of a model may be more unicorn than result, though it may be a beautiful, thought-provoking, rare event and worthy of study despite its singularity. To make unicorns universal, you cannot just run lots of computational experiments with lots of parameter values. Instead, you should do statistical tests of robustness or use robustness programs such as Active Nonlinear Testing (ANT) (23). In ANTs you can evolve parameter settings in an attempt to disrupt your findings. Of course, if a portion of your findings can be proven, then do so. In a model that generates six results, five of which can be proven, the sixth is likely to be true as well.

Viagra: Complex adaptive system models often include reproduction. Reproduction occurs on many levels often simultaneously. The reason for using the term "Viagra" was not because I could think of no other relevant terms that began with V. I chose Viagra because it suggests the possibility of turning reproduction on and off. Computational models have many advantages, including the ability to toggle operators on and off. If you want to see the effects of reproduction, turn it off. What role do tags play? Turn them off and analyze the difference. Toggling enables good scientific exploration at a speedy pace.

Web: A great deal of information flows through webs (24). These webs can be social: Most people get jobs through people they know. Or they can be electronic: the Internet. I often get bored by articles that begin "The Internet will fundamentally change (blank)," but the fact is, it will. The relevance of studying networks is obvious. If information and ideas do flow over networks, then a deep understanding of who has what information and why requires looking at these webs. The aforementioned work of Padgett and Carl Simon's work on the transmission of AIDS both depend on webs.

X-Ray: General-purpose simulation programs like SWARM have built-in probes so that you can X-ray the objects at any moment in time. These online probes provide information about the system. Allowing you to identify trends and spot patterns. Suppose that your agents create their own artificial agent models. You could look into their models to see what the agents are thinking. And your agents' artificial agents could construct their own models as well. It could go on and on like that. You'd have to dig really deep before you eventually find Chris Langton.

Yesterday: In a computational model, you can rerun history. You can hold the butterflies' wings and see if history changes. You can even be more creative and run Jurassic Park experiments of the type done by a group I call PLATH (Palmer, LeBaron, Arthur, Taylor, and Holland) (25). In these experiments, successful prehistoric agents were placed in the future. These clever experiments may help us to uncover characteristics of robust strategies. Personally, I think that introducing only a few players misses the point. If one dinosaur appeared in modern France, the French would catch it, set up another museum (as if the Louvre isn't enough), and reap the benefits. If 300,000 dinosaurs were dropped into France, we'd all be drinking Californian and Australian wines and hoping that the beasts don't swim well.

Zebra: In the end (and we're at Z now), much of the promise of computational modeling resides in its ability to help us identify patterns. Regions of black and white can be found in the neighborhoods of Chicago as well as on the hides of animals—animals, incidentally, that have proven largely untamable. If anything, humans are too good at creating patterns. We often see order in randomness. Now, many economists would have you believe that any pattern that could be profitably exploited would not last long (26). This would be true only if that pattern could be recognized, if agents had the requisite information. Quite possibly, many patterns exist that we miss, like the man who spoke in rhyme but was unaware of it. Further, once we recognize the patterns and change our behavior to account for the exploitable opportunity, we may create other patterns that we cannot recognize. There may even be a pattern of patterns, and patterns cubed.

I'm getting ahead of myself. Next time you are in a busy restaurant, watch the elaborate dance of the workers. The busboys, wait staff, and hostesses will roam the dining room floor yet never bump into one another. You can often identify patterns (of course you may be recognizing patterns that do not exist). These patterns evolved in the complex adaptive system of the restaurant. We can then try to ascertain properties of the patterns: Are they efficient? Stable? Robust to changes in the architecture of the restaurant? Complex systems research has helped to identify the causes of patterns. Particularly influential has been work on self-organized criticality (27)—the tendency for some systems to organize into critical states so that relaxation event sizes satisfy a power law distribution. Scientific exploration itself has patterns. One of those patterns appears to be the rise of computational models.

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