Predicting the Unpredictable

by Eric Bonabeau

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The collective behavior of people in crowds, markets, and organizations has long been a mystery. Now, some companies are finding ways to analyze, and even foretell, such "emergent phenomena."

by Eric Bonabeau

THREE YEARS AGO, Nasdaq faced a prickly problem. It wanted to reduce the tick size of its trading, which was then 1/8 of a dollar, to 1/16 and eventually down to 1/100. Among market professionals, the perceived wisdom was that the change would let buyers and sellers negotiate in more precise terms, thus driving down the market's spread between bid and ask prices. But the organization was wary that the move toward decimalization might backfire, leading to inefficiencies or, worse, loopholes that people could abuse. In the past, Nasdaq executives had analyzed the financial marketplace through economic studies, financial models, and other research. But the move to a smaller tick size was unknown territory that defied traditional analyses. How could Nasdaq ensure that decimalization would not muck up the system?

To answer that, Nasdaq worked with BiosGroup, a consultancy in Santa Fe, New Mexico, to develop a computer program that simulated the proposed changes. It was no ordinary program; the software created thousands of virtual individuals to represent market makers, institutional investors, pension fund managers, day traders, casual investors, and other market participants. Each of those software agents made decisions to buy and sell using real-world strategies. The technology, called agent-based modeling, enabled Nasdaq to explore stock market dynamics that pure mathematical methods could never unpick.

The results were eye-opening. A smaller tick size could actually *reduce* the market's ability to perform price discovery, leading to wider spreads between the bid and ask prices. Further tests helped Nasdaq confirm and understand this counterintuitive behavior, which allowed the organization to better plan its transition to decimalization.

Nasdaq is not the only pioneer to benefit from agent-based modeling. Macy's, for instance, has used the technology to investigate better ways to design its department stores. Hewlett-Packard has run agent-based simulations to anticipate how changes in its hiring strategy would affect its corporate culture. And Société Générale has used the technology to determine the operational risk of its asset management group.

Why Emergent Phenomena Are Important

To appreciate the full power of agent-based modeling, you first need to understand the concept of "emergent phenomena," and the best way to do that is by thinking of a traffic jam. Although they are everyday occurrences, traffic jams are actually very complicated and mysterious. On an individual level, each driver is trying to get somewhere and is following (or breaking) certain rules, some legal (the speed limit) and others societal or personal (slow down to let another driver change into your lane). But a traffic jam is a separate and distinct entity that *emerges* from those individual behaviors. Gridlock on a highway, for example, can travel backward for no apparent reason, even as the cars are moving forward.

Emergent phenomena are not just academic curiosities; they lie beneath the surface of many mysteries in the business world. How prices are set in a free market is but one illustration. Why, for example, do employee bonuses and other incentives sometimes lead to reduced productivity? Why do some products–like collapsible scooters–generate tremendous buzz, seemingly out of nowhere, while others languish, despite their multimillion-dollar marketing campaigns? How could a simple clerical error snowball into a catastrophic loss that bankrupts a financial institution?

For many businesses–and for society in general–emergent phenomena have become more prevalent in recent years. One reason is that cities and other urban areas have gotten more crowded. In addition, people are now interconnected to a greater degree (thanks, in part, to the Internet and other communications technologies). As population densities and the number of interactions among people increase, so does the probability of emergent phenomena. Furthermore, some businesses are becoming much more interconnected and complicated. The complexity of the stock market, for instance, has surged with a greater number of participants, including casual investors, and with the creation of sophisticated financial instruments like derivatives.

Because of their very nature, emergent phenomena have been devilishly difficult to analyze, let alone predict. Traditional approaches like spreadsheet and regression analyses or even system dynamics (a popular business-modeling technique that relies on sets of differential equations) are currently impotent in analyzing and predicting them. Such approaches work from the top down, taking global equations and frameworks and applying them to a situation, whereas the behavior of emergent phenomena is formed from the bottom up, starting with the local interactions of the different independent agents. Those individuals (such as the drivers in a traffic jam) alter their actions in response to what others are doing, and together the myriad interactions result in a group behavior (the traffic jam) that can easily elude any top-down analysis.

Emergent phenomena often defy intuition as well. Nasdaq's smaller tick size could lead to a larger bid-ask spread. Adding new lanes to a highway often makes rush-hour traffic jams far worse–a result known as Braess's paradox after the German operations research engineer who discovered it in 1968. People usually have no shortage of explanations for such surprising behavior ("Of course adding a lane will increase traffic jams because drivers will change lanes more often, slowing down other drivers"). Notwithstanding such convenient post-rationalizations, the crucial point here is that each emergent phenomenon is a unique entity that can be counterintuitive and, hence, difficult to predict.

In my experience studying a variety of emergent phenomena, I have found that the only way to analyze and even begin to predict them is to model them from the bottom up. In such a simulation, each individual participant, such as an investor buying stocks or a person driving on the highway, is a virtual person who makes decisions based on what the others are doing. Such modeling can accurately capture reality by making each participant a distinct individual. An experienced pension fund manager, after all, does not buy and sell stocks in the same way a young day trader does. In other words, modeling the agents as individuals helps capture the heterogeneity of the real world. And obtaining that kind of accuracy has recently become much more economical, thanks to cheaper computers and better modeling techniques.

Influencing Consumers

Indeed, cost-effective computing power has enabled companies to investigate what-if scenarios *in silico* that would be prohibitively expensive and risky to explore in the real world. Consider how traffic patterns – the way people move through stores and malls – can have a direct impact on business. In retail environments, what layout maximizes not only customers' satisfaction but also their spending?

To answer that, researchers have taken advantage of a wealth of existing information, including the copious bar-coded data collected at cash registers (what customers bought and the time they bought it) as well as the knowledge of experts like Paco Underhill, a naturalist of shopping behavior and the author of *Why We Buy.* Underhill knows, for ex-

Eric Bonabeau *is the chief scientist of Icosystem, a strategy consulting firm based in Cambridge, Massachusetts, that applies the tools of complexity science to the discovery of business opportunities. He can be reached at eric@icosystem.com.*

ample, the exact percentage of shoppers who turn right after entering a supermarket and the likelihood that someone will make a U-turn in the middle of a crowded aisle. Using this information, researchers can build agent-based models of, for instance, a supermarket with virtual shoppers. These simulations have found that changes in store layout have the potential to increase customer spending by up to 20%.

The independent actions of myriad people often result in a global behavior that bubbles up from their local actions.

Sainsbury's, the British supermarket chain, has developed such a computer model of its supermarket at South Ruislip in West London. With the help of Ugur Bilge of SimWorld, a London-based consultancy, and John Casti of the University of Vienna, Sainsbury's was able to incorporate sophisticated details into the model, such as how long each shopper spends in different departments. Camera studies have found, for example, that the average time a customer spends on buying milk is five seconds, versus 90 seconds for selecting a bottle of wine.

In the agent-based model, each shopper has a different list of items (based on real data collected from the bar code readers at the cash registers in the Sainsbury's stores). As the virtual people make their way through the aisles and choose their goods, the software tracks the customer densities throughout the store as well as the wait times at the checkout counters. Different layouts (such as relocating the frozen foods department) can be tested easily to judge their impact on store congestion.

Of course, enhancing the efficiency of shopping is not the only criterion. Store managers often want to separate high-traffic areas (the meat and baked goods sections, for example) to encourage impulse buying as shoppers travel between them. Sometimes "hot spots" (areas of congestion) are desirable locations for sale items or free samples. Furthermore, responding to customer psychology is important. A supermarket might want to place its produce section near the entrance, for instance, to impress customers with the freshness of its vegetables and fruits.

The agent-based model enabled Sainsbury's to balance those different factors in order to determine the best store layout. Although the project requires further refinement (the simulation does not take into account that younger customers tend to shop faster than older ones, for example), some of the preliminary results have given Sainsbury's insights into its business. In particular, the model exposed some surprising behavior. An increase in the number of customers in the store, for instance, can lead to a drop in wine sales. The reason is that, as the supermarket becomes crowded, the number of hot spots increases, which discourages customers from making their way to the wine section, located at a far corner of the store.

Other retailers have also used agent-based simulation to investigate better layouts for their stores. Specifically, Macy's was interested in such issues as where best to locate its cash registers and service desks – decisions that had been based on aesthetics and past practices. Working with Pricewaterhouse-Coopers (then Coopers & Lybrand), Macy's developed a virtual store that could be modified not only in terms of physical layout but also with respect to staffing – the number of sales associates in the different departments. A huge benefit of the agent-based model was that it enabled Macy's to experiment with different layouts and options in cyberspace without risking its reputation in the real world.

Consumer goods manufacturers are interested in agent-based modeling for a different reason. Companies like Procter and Gamble and Unilever would like to determine the optimal shelf placement for their products to make the most sales. Agent-based modeling can also be used to design better stadiums, shopping malls, and amusement parks.

In an example of the latter, Rob Axtell and Josh Epstein of the Brookings Institution have developed an agent-based model of a theme park that takes advantage of the facility's copious data from people counters, queue timers, customer surveys, and other sources. That information helped Axtell and Epstein build a detailed model of a heterogeneous population that had different desires and expectations for a day at the park. For instance, a family of four will have very different needs (six rides, four hot dogs, two cotton candies, three trips to the restroom) than a teenage couple on a date. The agent-based model considered that information to balance customer satisfaction with the theme park's goal of increasing business. The model was able to explore complex questions that were beyond the reach of traditional mathematical techniques and a pure statistical analysis of the data. (For instance, what's a better solution, extending the park's hours by 30 minutes or shortening each ride by 8.5 seconds?) Furthermore, the research sparked new ideas for further investigation. What would happen, for example, if every customer were given a small handheld computing device that displayed up-to-date information on line lengths at every ride and attraction?

Motivating Employees

Companies have been using agent-based technology to model the actions not only of their customers but also of their employees. A consumer goods corporation has used the technology to design a better incentive structure for its country managers in Europe. The company had been rewarding them based on their proportion of "shorts" (when a product sells out) – the lower the better. But that encouraged managers to order more than they needed – a particularly costly practice when the products were perishable. To prevent spoilage, the company often had to quickly relocate huge quantities of stock from, say, Denmark to Italy if the Danish country manager had overestimated his requirements. Thus a new incentive system was needed, one that would motivate the country managers to act in the best interest of the overall company.

The problem is trickier than it might first appear. Obviously, the current system encouraged hoarding, but incentives tied to just the company's overall performance were not viable because people dislike having their bonuses linked to factors over which they have little influence. So what local behavior should the company reward, and how should it ensure that the new system would not ultimately lead to any counterproductive actions, like hoarding? Agent-based modeling helped uncover the answer: Tie the country managers' bonuses directly to their storage costs in addition to their shorts. This change alone could reduce supply-chain costs by several percent, resulting in annual savings of millions of dollars. In essence, agent-based modeling helped connect the local behavior of country managers to the global performance of the organization.

Other companies have used agent-based modeling to investigate radically new ways of doing business. In the pharmaceutical industry, the cost of developing new drugs has surged, forcing many companies to rethink their R&D operations. Part of the problem is the so-called selfish-team syndrome, in which a group that is developing a particular drug makes biased decisions – for example, trying to save the project when it should be killed – because the team's reputation is tied to the drug's success or because the team members have become emotionally attached to the project. Such counterproductive behavior can slow drug development and increase its cost. Concerned by such issues, a major pharmaceutical company thought of a possible solution – creating a marketplace to subcontract some of the drug development in the early phases of human clinical trials.

To explore that and other alternatives, my colleagues at Icosystem and I developed an agent-based model of the various players, both the company's employees as well as potential contrac-

What Are Emergent Phenomena?

Whenever I try to explain the concept of emergent phenomena to a group of business executives, I ask them to think about the following game: Imagine that we all started mingling, as if we were at a cocktail party. At random, you silently pick two other people (call them A and B) and then you always position yourself so that A is between B and you. If everyone else were to do the same, what would happen? Now, let's change the game slightly: You always position yourself so that you are between A and B. Again, if everyone else were to do likewise, what would happen?

If there are several dozen of us, in the first game everyone will continue moving around the room for hours as we continuously try to keep ourselves in the right position. An outside observer who was unaware of our game might think that the movement was random. In the second scenario, the result is markedly different. Within seconds, we will have clumped into a single, almost stationary cluster. The same uninformed observer might think that our goal was to join together. In either case, our collective behavior – the milling around or the clumping – is the emergent phenomenon that has arisen from our individual actions. (To see a simulation of this game, visit www.icosystem.com/game.)

The simple game holds three important lessons. First, emergent phenomena can be unpredictable and often counterintuitive. What would happen, for example, if half of us followed the rule of the first game while the rest obeyed the other rule? Second, a seemingly minor change in what we do individually within a group can radically alter our collective behavior. Third, a logical link does not necessarily exist between our individual actions and the resulting emergent phenomenon. That is, why should the second – and not the first – game result in clumping?

Indeed, emergent phenomena often have a life of their own that is separate and distinct from the behaviors of their constituent parts. A traffic jam, for instance, cannot always be understood by studying what each individual driver is doing. Examples of emergent phenomena in the business world include organizational behavior that is shaped (or misshaped) through employee bonuses and incentives, free markets in which prices are set through the myriad interactions of buyers and sellers, and consumer buzz that propels sleeper products into runaway successes.

tors, including contract research organizations (companies that specialize in managing clinical trials), academics who do consulting work, and even experts at competing firms. We found that because of the diversity of the players (their different motivations, aversions to risk, cost structures, and so on), our pharmaceutical client could not possibly coordinate all of that activity profitably in an open marketplace.

Our client then suggested creating a network of participants, both internal and external, using incentives that encouraged better decision making (such as bonuses tied to the success of the entire portfolio of drug molecules). Through further modeling, we found that this solution could help our client more than double the risk-adjusted value of its portfolio of recently discovered molecules. Based on these results, the company has decided to test in the real world this new way of organizing early clinical development.

Agent-based modeling can also help predict how changes in an organization's recruiting strategy might ultimately affect its corporate culture. For instance, in an experimental project, Cap Gemini Ernst & Young's Center for Business Innovation developed an agent-based model of Hewlett-Packard's employees. For decades, HP had a strong tradition of hiring people for their loyalty and not necessarily for their experience. The company focused its efforts on finding people, often recent college graduates, who would fit into its culture, and many employees spent their entire careers at HP. But as the labor market began moving toward free agency, HP became concerned about how that change would affect the company. In addition, as the company shifted its focus toward services, it became increasingly interested in hiring high-powered, experienced consultants, who were typically much less loyal than HP engineers.

The simulation results confirmed some of HP's suspicions. Hiring free agents, for example, would eventually result in higher turnover costs, as employees (even those who were originally loyal) would begin to leave at a higher rate. A more surprising finding was that hiring experienced but less loyal people would eventually lead to an overall decrease in HP's total level of knowledge. That result would be particularly pronounced if the hiring strategy was changed abruptly. A better alternative was a gradual transition over the course of a year or two. Furthermore, the agent-based model suggested that HP could greatly mitigate the negative effects of such a change by simultaneously investing heavily in knowledge capture, such as a repository and IT systems that could retain some of the expertise of employees before they left. To do so would be a marked shift from HP's traditional focus on the development of each individual employee (for instance, by encouraging job rotation across businesses and functions) – a strategy that makes less sense when turnover is high.

Cost-effective computing power has enabled companies to investigate what-if scenarios in silico *that would be prohibitively expensive and risky to explore in the real world.*

An exciting new area of agent-based research is in the field of operational risk, which is a growing concern at many financial institutions because of the huge losses suffered over the years by Daiwa, Sumitomo, Barings, Kidder Peabody, and others. Although banks have developed efficient and sophisticated ways of assessing their market and credit risks, they are still in the early stages of figuring out just how to measure and monitor their operational risk. The task is extremely difficult because organizations do not have a clear understanding of exactly how an error (or act of fraud) can cascade through a system, causing a catastrophic loss, like a tree that falls on a power line and disrupts the electrical power grid of several states.

My colleagues at Bios and Cap Gemini Ernst & Young and I have applied agent-based modeling to analyze and quantify the operational risk of the asset management business of Société Générale in France. In the simulation, we modeled the company's employees as virtual agents who continually interacted with one another as they performed their tasks. From past data, we knew that bank employees commonly make certain types of errors, such as writing down the wrong number of zeroes ($10,000 instead of $1,000) or confusing a local currency with the euro. But we found that such errors would almost never lead to catastrophic losses *unless* they occurred in certain types of situations – for example, when the financial markets are volatile in August. Detailed results from the agent-based model helped explain why.

Fluctuations in the market lead to an increase in the volume of transactions, which then results in a much higher number of errors because people are rushed and have little time to double-check their work. In France, the problem is exacerbated in August because that's when many employees – generally the more experienced ones who have earned seniority – take extended vacations. In one scenario, an inexperienced and overworked trader makes a mistake: Instead of selling a stock, he buys it, and nobody in his department, including his busy supervisor, spots the error. The paperwork for the order makes its way to the back office, where a summer intern also fails to detect the mistake and processes the order. By the time the gaffe is uncovered several days later, the stock has plummeted in value, resulting in a multimillion-dollar loss.

Not only did we uncover such potential vulnerabilities, we could also estimate the likelihood that they would occur in the real world, using historical data from the capital markets. Although catastrophic losses were extremely unlikely in the model, by running thousands of simulations we were able to generate the rare events that triggered such disasters, and those results helped provide statistics about the bank's true operational risk. From that information, Société Générale could test procedures for minimizing that risk (such as changes to its vacation policy) as well as calculate how much capital it should set aside to cover certain potential losses. Currently, financial institutions do not have an accurate way of determining their operational risk, so regulatory agencies force them to overestimate the amount of rainy-day cash they need to have in reserve. In the asset-management business, a financial institution that could determine its operational risk accurately could easily save millions of dollars each year, not only by freeing up some rainy-day capital (which can then be invested) but also by lowering the organization's insurance premiums.

The research into organizational behavior at HP, our pharmaceutical client, and Société Générale holds a larger lesson. A common criticism of agent-based modeling is that the technology often requires an understanding of the complex psychology of human behavior, and errors in quantifying such "soft factors" can lead to results that are grossly inaccurate. As the saying goes, "garbage in, garbage out." Of course, an agent-based model will only be as accurate as the assumptions and data that went into it, but even approximate simulations can be very valuable. HP, for example, used its model to gain a better qualitative understanding of how certain factors (the company's hiring strategy, employee turnover, total level of knowledge, and so forth) were related. By contrast, the simulation for our pharmaceutical client was much more detailed and complete, enabling the company not only to understand its business better but also to predict, shape, optimize, and control it. In other words, how a company uses an agent-based model should be directly related to the work and data that went into building it, and vice versa.

The Bizarre World of Emergent Behavior

Emergent phenomena often behave in surprising and unpredictable ways. A classic example is Braess's paradox, named after the German engineer Dietrich Braess, who identified it in 1968. From extensive traffic studies, Braess found that adding new lanes to a highway does not necessarily reduce rush-hour gridlock but often makes it far worse. Indeed, emergent phenomena frequently exhibit counterintuitive behavior that can be difficult to understand. Consider the following:

- *A slight increase in the number of shoppers in a supermarket leads to a dramatic drop in sales of certain products.*
- *An organization that awards higher employee bonuses discovers a year later that corporate performance has plummeted.*
- *A sleeper product comes out of nowhere to become a blockbuster success, while a superior offering from a competitor languishes, despite a multimillion-dollar ad budget.*
- *After hiring dozens of experienced professionals, a company suffers a sharp decline in its total knowledge level.*

After studying such emergent phenomena for years, I have found that the only way to analyze them is through sophisticated computer simulations that model each person – such as the drivers on a highway or the different shoppers in a supermarket – as a distinct individual. These virtual people make decisions and respond to what the others are doing, and the myriad interactions then result in a collective group behavior that can be analyzed, predicted, shaped, and controlled.

The Emerging Future

"Where is the wisdom we have lost in knowledge? Where is the knowledge we have lost in information?" Those words were written in 1934 by T.S. Eliot in his poem "The Rock," but they still ring true. People today are awash in information, but does that make them necessarily any more knowledgeable – never mind wiser? Macy's, for example, has a mind-boggling amount of time-stamped data from its cash registers that could be used to replay entire days of shopping. But the company has struggled with ways to turn that information into knowledge. Bottom-up approaches like agent-based modeling are well suited for tasks like this, particularly when emergent properties are hidden in the data. That is, information about people and how they drive will not necessarily reveal anything about traffic jams until a tool like computer simulation frees that knowledge to bubble up.

Although agent-based modeling is relatively new, already companies are applying the technology to analyze some of their most perplexing problems. Indeed, researchers are discovering that, wherever there's an emergent phenomenon, agent-based modeling can help demystify it. For instance, Winslow Farrell, formerly a partner at PricewaterhouseCoopers's Emergent Solutions Group, and his team there applied the technology to help Twentieth Century Fox better understand consumer buzz. The goal of the project: Figure out how to time the release of a particular movie to maximize its chances of becoming a blockbuster.

Company strategy is another area that is ripe with opportunity, particularly with respect to game theory. Years ago, game theory was a fascinating field of economics that some people thought would revolutionize the study of strategy. But the theoretical limitations were daunting. Although game theory provided an excellent framework, real business situations were beyond what the theory could describe. Agent-based modeling enables researchers to drop the theory part of the field and simply play games to investigate, for example, what emergent phenomena will arise from the interactions of competitors, including companies that learn and adapt to the actions of others. At Icosystem, we have used agent-based modeling to investigate the market for Internet service providers. The simulation predicted both the emergence of free Internet service as well as the instability of that business model. That is, the first company that offers free service to consumers can differentiate itself from the pack and make money on advertising, but as competitors follow suit and begin slashing their monthly fees, the market collapses, eventually leading to sharp increases in subscription fees.

The potential of agent-based modeling should not be underestimated; the technology could completely revolutionize certain fields. The first time I presented the results of the Société Générale model to an audience of accountants and auditors, I had an epiphany – and so did my audience. Agent-based modeling is not just an effective way to determine risk in an organization, it is the best approach because individual employees (and not processes) are the ones making errors and committing fraud. For example, it is more natural – and precise – to say that an inexperienced clerk in accounting made a mistake by sending the wrong invoice to a customer than to say that the receivables process was impacted by an error event in the invoicing subprocess. Agent-based modeling promises to revolutionize business risk assessment because it constitutes a paradigm shift from spreadsheet- and process-oriented approaches. I predict that within five to ten years, agent-based modeling will be used routinely in audits.

An error can cascade through a system, causing a catastrophic loss, like a tree that falls on a power line and disrupts the electrical power grid of several states.

Other researchers are pushing agent-based modeling into an entirely new frontier. Instead of simulating what happens in the real world, they are creating their own reality in cyberspace by building software agents such as "shopbots" that roam through the Internet looking for the cheapest prices of products. As those agents become more intelligent and sophisticated, they could gather, trade, and translate information for us; they might even negotiate on our behalf. Jeffrey Kephart and his colleagues at IBM's Thomas J. Watson Research Center have built extensive computer models of such shopbots, "pricebots" (deployed by a merchandiser to undercut competitors' prices), and other software agents to predict the market dynamics of their emergent behavior.

But the business world is hardly alone in applying agent-based modeling to study emergent phenomena. Thanks to the technology, archeologists and social scientists are gaining a better understanding of the growth and decline of ancient cultures, epidemiologists are learning how diseases can spread quickly through a population, the U.S. military has explored better combat strategies for the battlefield, and the U.S. government is studying the flow of illegal drugs from South America to Florida in hopes of developing more effective policies to curtail smuggling. Indeed, agent-based modeling has enabled researchers from a wide range of fields to analyze problems that once seemed intractable. Perhaps more important, though, it has challenged the fundamental assumption that our complex world can always be understood best through top-down approaches.

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