ESSAY

Economics needs a scientific revolution

Financial engineers have put too much faith in untested axioms and faulty models, says **Jean-Philippe Bouchaud**. To prevent economic havoc, that needs to change.

D. PARKINS

Compared with physics, it seems fair to say that the quantitative success of the economic sciences has been disappointing. Rockets fly to the Moon; energy is extracted from minute changes of atomic mass. What is the flagship achievement of economics? Only its recurrent inability to predict and avert crises, including the current worldwide credit crunch.

Why is this so? Of course, to paraphrase Isaac Newton, modelling the madness of people is more difficult than modelling the motion of planets. But statistical regularities should emerge in the behaviour of large populations, just as the law of ideal gases emerges from the chaotic motion of individual molecules. To me, the crucial difference between modelling in physics and in economics lies rather in how the fields treat the relative role of concepts, equations and empirical data.

Classical economics is built on very strong assumptions that quickly become axioms: the rationality of economic agents (the premise that every economic agent, be that a person or a company, acts to maximize his profits), the 'invisible hand' (that agents, in the pursuit of their own profit, are led to do what is best for society as a whole) and market efficiency (that market prices faithfully reflect all known information about assets), for example. An economist once told me, to my bewilderment: "These concepts are so strong that they supersede any empirical observation." As economist Robert Nelson argued in his book, *Economics as Religion* (Pennsylvania State Univ. Press, 2002), the marketplace has been deified.

> **"Classical economics has no framework through which to understand 'wild' markets."**

Physicists, on the other hand, have learned to be suspicious of axioms. If empirical observation is incompatible with a model, the model must be trashed or amended, even if it is conceptually beautiful or mathematically convenient. So many accepted ideas have been proven wrong in the history of physics that physicists have grown to be critical and queasy about their own models.

Unfortunately, such healthy scientific revolutions have not yet taken hold in economics, where ideas have solidified into dogmas. These are perpetuated through the education system: students don't question formulas they can use without thinking. Although numerous physicists have been recruited by financial institutions over the past few decades, they seem to have forgotten the methodology of the natural sciences as they absorbed and regurgitated the existing economic lore.

The supposed omniscience and perfect efficacy of a free market stems from economic work done in the 1950s and 1960s, which with hindsight looks more like propaganda against communism than plausible science. In reality, markets are not efficient, humans tend to be over-focused in the short-term and blind in the long-term, and errors get amplified, ultimately leading to collective irrationality, panic and crashes. Free markets are wild markets.

Picture imperfect

Reliance on models based on incorrect axioms has clear and large effects. The Black–Scholes model, for example, which was invented in 1973 to price options, is still used extensively. But it assumes that the probability of extreme price changes is negligible, when in reality, stock prices are much jerkier than this. Twenty years ago, unwarranted use of the model spiralled into the worldwide October 1987 crash; the Dow Jones index dropped 23% in a single day, dwarfing recent market hiccups. Ironically, it was the very use of a crash-free model that helped to trigger a crash.

This time, the problem lies, in part, in the development of structured financial products that packaged subprime risk into seemingly respectable high-yield investments. The models used to price them were fundamentally flawed: they underestimated the probability that multiple borrowers would default on their loans simultaneously. These models again neglected the very possibility of a global crisis, even as they contributed to triggering one.

Surprisingly, classical economics has no framework through which to understand 'wild' markets, even though their existence is so obvious to the layman. Physics, on the other hand, has developed several models that explain how small perturbations can lead to wild effects. The theory of complexity shows that although a system may have an optimum state, it is sometimes so hard to identify that the system never settles there. This optimum state is not only elusive, it is also hyper-fragile to small changes in the environment, and therefore often irrelevant to understanding what is going on. There are good reasons to believe that this paradigm should apply to economic systems in general and financial markets in particular. We need to break away from classical economics and develop completely different tools. Some behavioural economists and econo-physicists are attempting to do this now, in a patchy way, but their fringe endeavour is not taken seriously by mainstream economics.

While work is done to enhance models, regulation also needs to improve. Innovations in financial products should be scrutinized, crash-tested against extreme scenarios outside the realm of current models and approved by independent agencies, just as we have done with other potentially lethal industries (chemical, pharmaceutical, aerospace, nuclear energy).

Crucially, the mindset of those working in economics and financial engineering needs to change. Economics curricula need to include more natural science. The prerequisites for more stability in the long run are the development of a more pragmatic and realistic representation of what is going on in financial markets, and to focus on data, which should always supersede perfect equations and aesthetic axioms. ■

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A model approach

More development work is needed to help computer simulations inform economic policy.

Models are everywhere in economics. They range from the pencil-and-paper equations used for academic analyses of market behaviour, to the computer forecasts used by central banks, such as the Bank of England and the US Federal Reserve System, to determine the likely effects of interest-rate adjustments.

But the reputation of economic models has been tarnished of late. Virtually none anticipated the global financial meltdown that began two years ago this summer (see pages 680 and 685). The finger-pointing seems likely to go on indefinitely: were the models flawed? Or were policy-makers at fault for ignoring the warnings?

What is clear is that economic models need to improve. The ability to run policy options through a believable set of 'what-if' scenarios could be useful to forestall future economic crises, and to inform debate, such as that over the labyrinthine efforts to reform the US health-care system.

The field could benefit from lessons learned in the large-scale modelling of other complex phenomena, such as climate change and epidemics (see page 687). Those lessons, taken together with lessons from the downturn, suggest an ambitious research agenda — not just for economists, but for psychologists, political and social scientists, computer researchers and more.

First, details matter. Government regulators rely on dynamic stochastic general equilibrium (DSGE) simulations, which can make sophisticated extrapolations of past economic data. But these models do little to incorporate information about the financial sector, which is where the current crisis began. Which company was entering into what kind of arrangements with another, for example, and how were they all interconnected? And most models don't even attempt to incorporate the psychological insights gained from behavioural economics, and so ignore shifting attitudes towards risk, and the spread of fear — both major contributors to the crisis. The comparatively few modelling efforts that do try to include these factors deserve support — and many more such efforts are needed.

Second, models should evolve through vigorous competition. As the articles in this issue show, advocates of agent-based modelling techniques, which represent each individual or company with an 'agent', claim that their programs can often account for economic phenomena much better than can DSGE simulations. Such claims need to be addressed empirically. The economics community should try to agree on a standard set of test cases analogous to those used by climate modellers, whose challenges can include being able to reproduce El Niño oscillations. Economic modellers should also consider adopting the modular architecture used in many climate models. This approach makes it easy to aggregate smaller models into more comprehensive simulations, while still allowing steady improvement in each piece. A sub-model for ocean circulation, say, can be switched for an alternative circulation module without changing anything else.

Third, modellers seeking to make a real difference in the world should concentrate on the tangible, immediate questions that decision-makers actually worry about. A good example to follow is that of pandemic planning, in which simulations are already in widespread use to help officials decide when to close schools and other public gathering places, and how best to mount a vaccination campaign. The simulations alone cannot answer such questions, nor can they replace judgement. But by helping officials frame the problem, organize the available information and identify which factors matter, they can make judgements better informed. ■

Science under attack

Congress should stop playing politics with the peer-review process.

In a depressingly familiar display of irresponsible politicking, the US House of Representatives has taken aim at three studies funded by the National Institutes of Health (NIH). Representative Darrell Issa (Republican, California) introduced an amendment killing the projects on 24 July, during a debate on the NIH's 2010 budget. The House passed the amendment by a voice vote.

Issa was unhappy that the studies looked at substance abuse and HIV risk behaviour, and that the subjects were outside the United States. One focused on Russian alcoholics, another on female sex workers in China and a third on female and transgender prostitutes in Thailand. All three passed muster with NIH peer reviewers, and together would cost about $5 million over five years. Issa wanted that money to be spent at home, and complained that HIV had been heavily studied already. But his reasoning is specious: alcoholism, prostitution and HIV do not respect borders, and any behavioural information that could help slow the transmission of HIV is crucial. Some 33 million people are infected worldwide, and a vaccine is nowhere in sight.

Issa's tactic is not new. Since 2003, conservative House Republicans have tried at least five times to strip funding from peer-reviewed projects that drew their ire. Such meddling threatens to undermine the peer-review process as well as potentially eroding the public's trust that science is above politics.

Also worrying is the House Democrats' acquiescence to Issa's amendment. Democrats facing tough re-election bids hoped to dodge Republican attacks in media adverts in their home districts that might have resulted from opposing Issa. Their assumption is that the amendment can be quietly removed when House and Senate negotiators meet to square their versions of the NIH bill before a final vote on it. But Congress should renounce all tactics that undermine peer review — and cease indulging those who use them. ■

OPINION

The economy needs agent-based modelling

The leaders of the world are flying the economy by the seat of their pants, say **J. Doyne Farmer** and **Duncan Foley**. There is, however, a better way to help guide financial policies.

In today's high-tech age, one naturally assumes that US President Barack Obama's economic team and its international counterparts are using sophisticated quantitative computer models to guide us out of the current economic crisis. They are not.

The best models they have are of two types, both with fatal flaws. Type one is econometric: empirical statistical models that are fitted to past data. These successfully forecast a few quarters ahead as long as things stay more or less the same, but fail in the face of great change. Type two goes by the name of 'dynamic stochastic general equilibrium'. These models assume a perfect world, and by their very nature rule out crises of the type we are experiencing now.

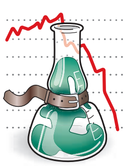
As a result, economic policy-makers are basing their decisions on common sense, and on anecdotal analogies to previous crises such as Japan's 'lost decade' or the Great Depression (see *Nature* **457,** 957; 2009). The leaders of the world are flying the economy by the seat of their pants.

P. NOBLE/REUTERS

Agent-based models could help to evaluate policies designed to foster economic recovery.

This is hard for most non-economists to believe. Aren't people on Wall Street using fancy mathematical models? Yes, but for a completely different purpose: modelling the potential profit and risk of individual trades. There is no attempt to assemble the pieces and understand the behaviour of the whole economic system.

There is a better way: agent-based models. An agent-based model is a computerized simulation of a number of decision-makers (agents) and institutions, which interact through prescribed rules. The agents can be as diverse as needed — from consumers to policy-makers and Wall Street professionals — and the institutional structure can include everything from banks to the government. Such models do not rely on the assumption that the economy will move towards a predetermined equilibrium state, as other models do. Instead, at any given time, each agent acts according to its current situation, the state of the world around it and the rules governing its behaviour. An individual consumer, for example, might decide whether to save or spend based on the rate of inflation, his or her current optimism about the future, and behavioural rules deduced from psychology experiments. The computer keeps track of the many agent interactions, to see what happens over time. Agent-based simulations can handle a far wider range of nonlinear behaviour than conventional equilibrium models. Policy-makers can thus simulate an artificial economy under different policy scenarios and quantitatively explore their consequences.



RECESSION WATCH

Why is this type of modelling not well-developed in economics? Because of historical choices made to address the complexity of the economy and the importance of human reasoning and adaptability.

The notion that financial economies are complex systems can be traced at least as far back as Adam Smith in the late 1700s. More recently John Maynard Keynes and his followers attempted to describe and quantify this complexity based on historical patterns. Keynesian economics enjoyed a heyday in the decades after the Second World War, but was forced out of the mainstream after failing a crucial test during the mid-seventies. The Keynesian predictions suggested that inflation could pull society out of a recession; that, as rising prices had historically stimulated supply, producers would respond to the rising prices seen under inflation by increasing production and hiring more workers. But when US policy-makers increased the money supply in an attempt to stimulate employment, it didn't work — they ended up with both high inflation and high unemployment, a miserable state called 'stagflation'. Robert Lucas and others argued in 1976 that Keynesian models had failed because they neglected the power of human learning and adaptation. Firms and workers learned that inflation is just inflation, and is not the same as a real rise in prices relative to wages.

Realistic behaviour

The cure for macroeconomic theory, however, may have been worse than the disease. During the last quarter of the twentieth century, 'rational expectations' emerged as the dominant paradigm in economics. This approach assumes that humans have perfect access to information and adapt instantly and rationally to new situations, maximizing their long-run personal advantage. Of course real people often act on the basis of overconfidence, fear and peer pressure — topics that behavioural economics is now addressing.

But there is a still larger problem. Even if rational expectations are a reasonable model of human behaviour, the mathematical machinery is cumbersome and requires drastic simplifications to get tractable results. The equilibrium models that were developed, such as those used by the US Federal Reserve, by necessity stripped away most of the structure of a real economy. There are no banks or derivatives, much less sub-prime mortgages or credit default swaps — these introduce too much nonlinearity and complexity for equilibrium methods to handle. When it comes to setting policy, the predictions of these models aren't even wrong, they are simply non-existent (see *Nature* **455,** 1181; 2008).

Agent-based models potentially present a way to model the financial economy as a complex system, as Keynes attempted to do, while taking human adaptation and learning into account, as Lucas advocated. Such models allow for the creation of a kind of virtual


S. PLATT/GETTY IMAGES

universe, in which many players can act in complex — and realistic — ways. In some other areas of science, such as epidemiology or traffic control, agent-based models already help policy-making.

Promising efforts

There are some successful agent-based models of small portions of the economy. The models of the financial market built by Blake LeBaron of Brandeis University in Waltham, Massachusetts, for example, provide a plausible explanation for bubbles and crashes, reproducing liquidity crises and crashes that never appear in equilibrium models. Rob Axtell of George Mason University in Fairfax, Virginia, has devised firm dynamics models that simulate how companies grow and decline as workers move between them. These replicate the power-law distribution of company size that one sees in real life: a very few large firms, and a vast number of very small ones with only one or two employees.

Other promising efforts include the credit-sector model of Mauro Gallegati's group at the Marche Polytechnic University in Ancona, Italy, and the monetary model developed by Robert Clower of the University of South Carolina in Columbia and Peter Howitt of Brown University in Providence, Rhode Island. These models are very useful, but their creators would be the first to say that they provide only a tentative first step.

To see in more detail how an agent-based model works, consider the model that one of us (Farmer) has developed with Stefan Thurner of the University of Vienna and John Geanakoplos of Yale University to explore how leverage affects fluctuations in stock prices (published in a Santa Fe Institute working paper). Leverage, the investment of borrowed funds, is measured as the ratio of total assets owned to the wealth of the borrower; if a house is bought with a 20% down-payment the leverage is five. There are four types of agents in this model. 'Noise traders', who trade more or less at random, but are slightly biased toward driving prices towards a fundamental value; hedge funds, which hold a stock when it is under-priced and otherwise hold cash; investors who decide whether to invest in a hedge fund; and a bank that can lend money to the hedge funds, allowing them to buy more stock. Normally, the presence of the hedge funds damps volatility, pushing the stock price towards its fundamental value. But, to contain their risk, the banks cap leverage at a predetermined maximum value. If the price of the stock drops while a fund is fully leveraged, the fund's wealth plummets and its leverage increases; thus the fund has to sell stock to pay off part of its loan and keep within its leverage limit, selling into a falling market.

> "The policy predictions of the models that are in use aren't wrong, they are simply non-existent."

This agent-based model shows how the behaviour of the hedge funds amplifies price fluctuations, and in extreme cases causes crashes. The price statistics from this model look very much like reality. It shows that the standard ways banks attempt to reduce their own risk can create more risk for the whole system.

Previous models of leverage based on equilibrium theory showed qualitatively how leverage can lead to crashes, but they gave no quantitative information about how this affects the statistical properties of prices. The agent approach simulates complex and nonlinear behaviour that is so far intractable in equilibrium models. It could be made more realistic by adding more detailed information about the behaviour of real banks and funds, and this could shed light on many important questions. For example, does spreading risk across many financial institutions stabilize the financial system, or does it increase financial fragility? Better data on lending between banks and hedge funds would make it possible to model this accurately. What if the banks themselves borrow money and use leverage too, a process that played a key role in the current crisis? The model could be used to see how these banks might behave in an alternative regulatory environment.

Agent-based models are not a panacea. The major challenge lies in specifying how the agents behave and, in particular, in choosing the rules they use to make decisions. In many cases this is still done by common sense and guesswork, which is only sometimes sufficient to mimic real behaviour. An attempt to model all the details of a realistic problem can rapidly lead to a complicated simulation where it is difficult to determine what causes what. To make agent-based modelling useful we must proceed systematically, avoiding arbitrary assumptions, carefully grounding and testing each piece of the model against reality and introducing additional complexity only when it is needed. Done right, the agent-based method can provide an unprecedented understanding of the emergent properties of interacting parts in complex circumstances where intuition fails.

A thorough attempt to understand the whole economy through agent-based modelling will require integrating models of financial interactions with those of industrial production, real estate, government spending, taxes, business investment, foreign trade and investment, and with consumer behaviour. The resulting simulation could be used to evaluate the effectiveness of different approaches to economic stimulus, such as tax reductions versus public spending.

Holistic approach

Such economic models should be able to provide an alternative tool to give insight into how government policies could affect the broad characteristics of economic performance, by quantitatively exploring how the economy is likely to react under different scenarios. In principle it might even be possible to create an agent-based economic model capable of making useful forecasts of the real economy, although this is ambitious.

Creating a carefully crafted agent-based model of the whole economy is, like climate modelling, a huge undertaking. It requires close feedback between simulation, testing, data collection and the development of theory. This demands serious computing power and multi-disciplinary collaboration among economists, computer scientists, psychologists, biologists and physical scientists with experience in large-scale modelling. A few million dollars — much less than 0.001% of the US financial stimulus package against the recession — would allow a serious start on such an effort.

Given the enormity of the stakes, such an approach is well worth trying. ■

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See Opinion, page 687, and Editorial, page 667.
Further reading accompanies this article online.

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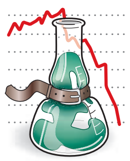
ILLUSTRATIONS BY JESSE LEFKOWITZ

Meltdown modelling

Could agent-based computer models prevent another financial crisis? **Mark Buchanan** reports.



RECESSION WATCH

It's 2016, and experts at a US government facility have detected a threat to national security. A screen on the wall maps the world's largest financial players — banks, governments and hedge funds — as well as the web of loans, ownership stakes and other legal claims that link them. High-powered computers have been using these enormous volumes of data to run through scenarios that flush out unexpected risks. And this morning they have triggered an alarm.

Flashing orange alerts on the screen show that a cluster of US-based hedge funds has unknowingly taken large ownership positions in similar assets. If one of the funds should have to sell assets to raise cash, the computers warn, its action could drive down the assets' value and force others to start selling their own holdings in a self-amplifying downward spiral. Many of the funds could be bankrupt within 30 minutes, creating a threat to the entire financial system. Armed with this information, financial authorities step in to orchestrate a controlled elimination of the dangerous tangle.

Alas, this story is likely to remain fiction. No government was able to carry out any such 'war room' analyses as the current financial crisis emerged, nor does the capability exist today. Yet a growing number of scientists insist that something like it is needed if society is to avoid similar crises in future.

Financial regulators do not have the tools they need to predict and prevent meltdowns, says physicist-turned-sociologist Dirk Helbing of the Swiss Federal Institute of Technology Zurich, who has spent the past two decades modelling large-scale human systems such as urban traffic or pedestrian flows. They can do a good job of tracking an economy using the statistical measures of standard econometrics, as long as the influences on the economy are independent of each other, and the past remains a reliable guide to the future. But the recent financial collapse was a 'systemic' meltdown, in which intertwined breakdowns in housing, banking and many other sectors conspired to destabilize the system as a whole. And the past has been anything but a reliable guide of late: witness how US analysts were led astray by decades of data suggesting that housing values would never simultaneously fall across the nation.

> **"We have had a massive failure of the dominant economic model."**
> — Eric Weinstein

Likewise, economists can get reasonably good insights by assuming that human behaviour leads to stable, self-regulating markets, with the prices of stocks, houses and other things never departing too far from equilibrium. But 'stability' is a word few would use to describe the chaotic markets of the past few years, when complex, nonlinear feedbacks fuelled the boom and bust of the dot-com and housing bubbles, and when banks took extreme risks in pursuit of ever higher profits.

In an effort to deal with such messy realities, a few economists — often working with physicists and others outside the economic mainstream — have spent the past decade or so exploring 'agent-based' models that make only minimal assumptions about human behaviour or inherent market stability (see page 685). The idea is to build a virtual market in a computer and populate it with artificially intelligent bits of software — 'agents' — that interact with one another much as people do in a real market. The computer then lets the overall behaviour of the market emerge from the actions of the individual agents, without presupposing the result.

Agent-based models have roots dating back to the 1940s and the first 'cellular automata', which were essentially just simulated grids of on–off switches that interacted with their nearest neighbours. But they didn't spark much interest beyond the physical-science community until the 1990s, when advances in computer power began to make realistic social simulations more feasible. Since then they have found increasing use in problems such as traffic flow and the spread of infectious diseases (see page 687). Indeed, points out Helbing, agent-based models are the social-science analogue of the computational simulations now routinely used elsewhere in science to explore complex nonlinear processes such as the global climate.

That is why he is eager to bring social and physical scientists together to develop computational 'wind tunnels' that would allow regulators to test policies before putting them into practice. "The idea is to invest a lot in science," he says, "and thereby save hundreds of times as much by avoiding or mitigating future crises."

Just more theory?

That notion is a tough sell among mainstream economists, many of whom are less than thrilled by offers of outside help. "After any crisis," says Paul Romer of Stanford University, California, a leading researcher in the economics of innovation, "you hear recommendations to recruit scientists from other fields who can purge economics and finance of ideology and failed assumptions. But we should ask if there is any evidence that more theory, developed by people who don't have domain experience, is the key to scientific progress in this area."

Others think some fresh thinking is long overdue. "We have had a massive failure of the dominant economic model," says Eric Weinstein, a physicist working in mathematical finance for the Natron Group, a hedge fund in New York, "and we're trying to find the right people to deal with this failure. At least some of those people are likely to be unfamiliar voices and come from other parts of science."

At least some economists agree. The meltdown has shown that regulatory policies have to cope with far-from-equilibrium situations, says economist Blake LeBaron of Brandeis University in Waltham, Massachusetts. "Even fairly simple agent-based models can be used as thought experiments to see if there is something that hasn't been considered by the policy-makers."

LeBaron has spent the past decade and a half working with colleagues, including a number of physicists, to develop an agent-based model of the stock market. In this model, several hundred agents attempt to profit by buying and selling stock, basing their decisions on patterns they perceive in past stock movements. Because the agents can learn from and respond to emerging market behaviour, they often shift their strategies, leading other agents to change their behaviour in turn. As a result, prices don't settle down into a stable equilibrium, as standard economic theory predicts. Much as in the real stock market, the prices keep bouncing up and down erratically, driven by an ever-shifting ecology of strategies and behaviours.

Nor is the resemblance just qualitative, says LeBaron. Detailed analyses of the agent-based model show that it reproduces the statistical features of real markets, especially their susceptibility to sudden, large price movements. "Traditional models do not go very far in explaining these features," LeBaron says.

Another often-cited agent-based model got its start in the late 1990s, as the NASDAQ stock exchange in New York was planning to stop listing its stock prices as fractions such as 12¼ and instead list them as decimals. The goal was to improve the accuracy of stock prices, but the change would also allow prices to move by smaller increments, which could affect the strategies followed by brokers with unknown consequences for the market as a whole. So before making this risky change, NASDAQ chief Mike Brown hired BiosGroup, a company based in Santa Fe, New Mexico, to develop an agent-based model of the market to test the idea.

"We still implement new economic measures without any prior testing." — Dirk Helbing

"Over ten years on the NASDAQ Board," says Brown, "I grew increasingly disappointed in our approach to studying the consequences of proposed market regulations, and wanted to try something different."

Once the model could reproduce price fluctuations in a mathematically accurate way, NASDAQ used it as a market wind tunnel. The tests revealed that if the stock exchange reduced its price increment too much, traders would be able to exploit strategies that would make them quick profits at the expense of overall market efficiency. Thus, when the exchange went ahead with the changeover in 2001, it was able to take steps to counter this vulnerability.

Agent-based models are also being used elsewhere in the private sector. For example, the consumer-products giant Proctor & Gamble of Cincinnati, Ohio, has used agent-based models to optimize the flow of goods through its network of suppliers, warehouses and stores. And Southwest Airlines of Dallas, Texas, has used agent-based models for routing cargo.

Despite such successes, however, financial regulators such as the US Securities and Exchange Commission (SEC) still don't use agent-based models as practical tools. "When the SEC changes trading rules, it typically has either flimsy or modest support from econometric evidence for the action, or else no empirical evidence and the change is driven by ideology," claims computational social scientist Rob Axtell of George Mason University in Fairfax, Virginia. "You have to wonder why Mike Brown is doing this, while the SEC isn't."

Risk of the new

A big part of the answer is that agent-based models remain at the fringe of mainstream economics, and most economists continue to prefer conventional mathematical models. Many of them argue that agent-based models haven't had the same level of testing.

Another problem is that an agent-based model of a market with many diverse players and a rich structure may contain many variable parameters. So even if its output matches reality, it's not always clear if this is because of careful tuning of those parameters, or because the model succeeds in capturing realistic system dynamics. That leads many economists and social scientists to wonder whether any such model can be trusted. But agent-based enthusiasts counter that conventional economic models also contain many tunable parameters and are therefore subject to the same criticism.

Familiarity wins out, notes Chester Spatt, former chief economist at the SEC. Regulators feel duty-bound to adhere to generally accepted and well-vetted techniques, he says. "It would be problematic for the rule-making process to use methods whose foundation or applicability were not established."

Still, agent-based techniques are beginning to enter the regulatory process. For example, decision-makers in Illinois and several other US states use computational models of complex electricity markets. They want to avoid a repeat of the disaster in California in 2000, when Enron and other companies, following market deregulation, were able to manipulate energy supplies and prices for enormous profit. Rich computational models have made it possible to test later market designs before putting them in place.

"We've had a lot of success in developing these models," says economist Leigh Tesfatsion of Iowa State University in Ames, who has led the development of an open-source agent-based model known as the AMES Wholesale Power Market Test Bed. "It has worked

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because we've focused on all the details of the real situation and can address questions that policy-makers really care about," she says.

Other models have successfully simulated financial markets. At Yale University, for example, economist John Geanakoplos, working with physicists Doyne Farmer of the Santa Fe Institute and Stefan Thurner of the Medical University of Vienna, has constructed an agent-based model exploring the systemic consequences of massive borrowing by hedge funds to finance their investments. In their simulations, the funds frequently get locked into a self-amplifying spiral of losses (see page 685) — much as real-world hedge funds did after August 2007.

> **"Experts' complementary knowledge could 'collide', creating new knowledge."**
> — Dirk Helbing

At the University of Genoa in Italy, meanwhile, Silvano Cincotti and his colleagues are creating an agent-based model of the entire European Union economy. Their model includes markets for consumer goods and financial assets, firms that interact with banks to obtain loans, and banks that compete with one another by offering different interest rates. Based on real economic data, the model currently represents some 10 million households, 100,000 firms and about 100 banks, all of which can learn and change their strategies if they find more profitable ways of doing business.

"We hope that these simulations will have an outstanding impact on the economic-policy capabilities of the European Union," says Cincotti, "and help design the best policies on an empirical basis."

This is the kind of ambition that has inspired Helbing. He doesn't pretend to be an economic modeller himself: since the early 1990s his own work has focused on simulations of human behaviour in relatively small groups — how traffic ebbs and flows through a road network, for example, or how crowds crush towards a door in a panic situation — as well as on experiments to test his predictions with real data. But that work has given Helbing a keen appreciation for the way complex collective phenomena can emerge from even the simplest individual interactions. If pedestrians can organize themselves into smoothly flowing streams just by trying to walk through a crowded shopping centre — as he has shown they do — just imagine how much richer the emergent phenomena must be in a group the size of a national economy.

Crisis logic

That observation acquired fresh force for Helbing after last year's global financial meltdown made it clear that a regulatory system based on conventional economic theory had failed.

"It's remarkable," he says, "that while any new technical device or medical drug has extensive testing for efficiency, reliability and safety before it ever hits the market, we still implement new economic measures without any prior testing."

To get around this impasse, he says, researchers need to reimagine the social and economic sciences on a larger scale. "I imagine experts from different fields meeting in one place for extended periods of time," he says, "so that their complementary knowledge could 'collide', creating new ideas, much as particle colliders create new kinds of particles." Ultimately, such an effort would bring together social scientists, economists, physicists, ecologists, computer scientists and engineers in a network of large centres for socioeconomic data mining and crisis forecasting, as well as in supercomputer centres for social simulation and wind-tunnel-like testing of policy.

That is a large ambition, Helbing admits — especially as he has only recently got tentative approval for a one-year grant from the European Commission to develop the idea. But now, in the aftermath of the meltdown, may be the time to start.

Axtell endorses that view. "Left to their own devices," he says, "academic macroeconomists will take a generation to make this transition. But if policy-makers demand better models, it can be accomplished much more quickly."

"The revolution has to begin here," agrees Weinstein, who helped organize a meeting in May at the Perimeter Institute for Theoretical Physics in Waterloo, Canada, that assembled the kind of interdisciplinary mix of experts that Helbing envisions. "And I think ideas from physics and other parts of science really have a chance to catalyse something remarkable." ■

Mark Buchanan is a science writer based in Cambridge, UK. After writing this story, he was involved in reviewing grant proposals on the topic of agent-based modelling.

See Editorial, page 667, and Opinion, pages 685 and 687.

Modelling to contain pandemics

Agent-based computational models can capture irrational behaviour, complex social networks and global scale — all essential in confronting H1N1, says **Joshua M. Epstein**.

As the world braces for an autumn wave of swine flu (H1N1), the relatively new technique of agent-based computational modelling is playing a central part in mapping the disease's possible spread, and designing policies for its mitigation.

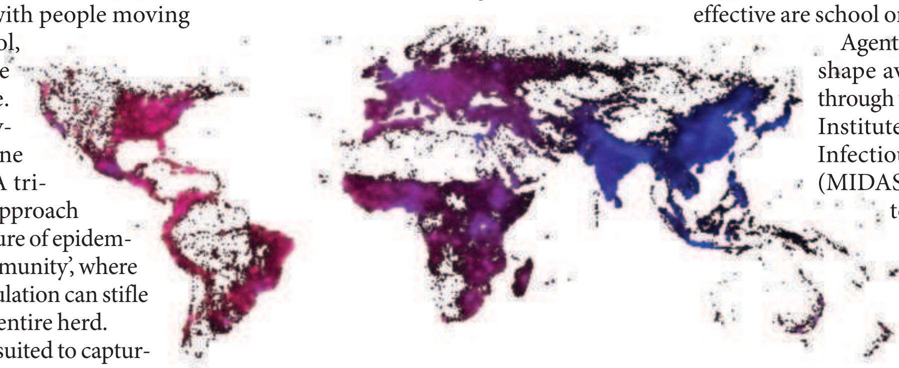
Classical epidemic modelling, which began in the 1920s, was built on differential equations. These models assume that the population is perfectly mixed, with people moving from the susceptible pool, to the infected one, to the recovered (or dead) one. Within these pools, everyone is identical, and no one adapts their behaviour. A triumph of parsimony, this approach revealed the threshold nature of epidemics and explained 'herd immunity', where the immunity of a subpopulation can stifle outbreaks, protecting the entire herd.

But such models are ill-suited to capturing complex social networks and the direct contacts between individuals, who adapt their behaviours — perhaps irrationally — based on disease prevalence.

Agent-based models (ABMs) embrace this complexity. ABMs are artificial societies: every single person (or 'agent') is represented as a distinct software individual. The computer model tracks each agent, 'her' contacts and her health status as she moves about virtual space — travelling to and from work, for instance. The models can be run thousands of times to build a robust statistical portrait comparable to epidemic data. ABMs can record exact chains of transmission from one individual to another. Perhaps most importantly, agents can be made to behave something like real people: prone to error, bias, fear and other foibles.

Such behaviours can have a huge effect on disease progression. What if significant numbers of Americans refuse H1N1 vaccine out of fear? Surveys and historical experience indicate that this is entirely possible, as is substantial absenteeism among health-care workers. Fear itself can be contagious. In 1994, hundreds of thousands of people fled the Indian city of Surat to escape pneumonic plague, although by World Health Organization criteria no cases were confirmed. The principal challenge for agent modelling is to represent such behavioural factors appropriately; the capacity to do so is improving through survey research, cognitive science, and quantitative historical study.

Robert Axtell and I published a full agent-based epidemic model[1] in 1996. Agents with diverse digital immune systems roamed a landscape, spreading disease. The model tracked dynamic epidemic networks, simple mechanisms of immune learning, and behavioural changes resulting from disease progression, all of which fed back to affect epidemic dynamics. However, the model was small (a few thousand agents) and behaviourally primitive.


Simulation of a pandemic beginning in Tokyo.

J. PARKER

Now, the cutting edge in performance is the Global-Scale Agent Model (GSAM)[2], developed by Jon Parker at the Brookings Institution's Center on Social and Economic Dynamics in Washington DC, which I direct. This includes 6.5 billion distinct agents, with movement and day-to-day local interactions modelled as available data allow. The epidemic plays out on a planetary map, colour-coded for the disease state of people in different regions — black for susceptible, red for infected, and blue for dead or recovered. The map pictured shows the state of affairs 4.5 months into a simulated pandemic beginning in Tokyo, based on a plausible H1N1 variant.

> "Agents can be made to behave something like real people: prone to error, bias, fear."

For the United States, the GSAM contains 300 million cyber-people and every hospital and staffed bed in the country. The National Center for the Study of Preparedness and Catastrophic Event Response at Johns Hopkins University in Baltimore is using the model to optimize emergency surge capacity in a pandemic, supported by the Department of Homeland Security.

Models, however, are not crystal balls and the simulation shown here is not a prediction. It is a 'base case' which by design is highly unrealistic, ignoring pharmaceuticals, quarantines, school closures and behavioural adaptations. It is nonetheless essential because, base case in hand, we can rerun the model to investigate the questions that health agencies face. What is the best way to allocate limited supplies of vaccine or antiviral drugs? How effective are school or work closures?

Agent-based models helped to shape avian flu (H5N1) policy, through the efforts of the National Institutes of Health's Models of Infectious Disease Agent Study (MIDAS) — a research network to which the Brookings Institution belongs. The GSAM was recently presented to officials from the Centers for Disease Control and Prevention in Atlanta, Georgia, and other agencies, and will be integral to MIDAS consulting on H1N1 and other emerging infectious diseases. In the wake of the 11 September terrorist attacks and anthrax attacks in 2001, ABMs played a similar part in designing containment strategies for smallpox.

These policy exercises highlight another important feature of agent models. Because they are rule-based, user-friendly and highly visual, they are natural tools for participatory modelling by teams — clinicians, public-health experts and modellers. The GSAM executes an entire US run in around ten minutes, fast enough for epidemic 'war games', giving decision-makers quick feedback on how interventions may play out. This speed may even permit the real-time streaming of surveillance data for disease tracking, akin to hurricane tracking. As H1N1 progresses, and new health challenges emerge, such agent-based modelling efforts will become increasingly important. ■

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1. Epstein, J. M. & Axtell, R. L. *Growing Artificial Societies: Social Science from the Bottom Up* Ch. V. (MIT Press, 1996).
2. Parker, J. A. *ACM Trans Model. Comput. S.* (in the press).

See Opinion, page 685, and Editorial, page 667.
Further reading accompanies this article online.