# QUANTUM COMPUTING AND THE LEGAL IMAGINATION

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## QUANTUM ADVANTAGE

Quantum computing promises to open new fields to fast, flexible, and powerful computation. The power of a relatively modest quantum computer by certain measures will far exceed that of any conventional computer in existence today. The quantum computer works in a completely different way from classical computers, using quantum bits (qubits), quantum logic, and quantum algorithms.[1] Quantum computing represents one of the most exciting new technologies to emerge this century—and we have every reason to expect that the capabilities presented by quantum computers will create new legal and regulatory possibilities, as well as enable new tools for use by lawyers and judges in the practice of law.

Like artificial intelligence—or better, together with artificial intelligence—quantum computing will impact the practice of law along a number of visible fronts. Quantum computing will

- Enable new legal tools for use by lawyers, judges, and regulators;
- Enable nonlawyers to directly access legal services;
- Improve legal information retrieval;
- Permit models of complex social and economic relations that can be used to reach legal determinations;
- Encourage the growth of particular areas of law now hindered by complexity;
- Raise new legal, ethical, and distributional challenges; and
- Stimulate the legal imagination to reach new and initially strange insights and understandings;

The implementation of quantum computing, across all fields, including law, will depend on the location of "quantum" advantage, such as identifying those particular applications where quantum computers will outperform conventional computers.[2]

Quantum computers work in a fundamentally different way than do conventional (or "classical") computers. Indeed, quantum computers will be faster and more powerful than classical computers in performing certain computations, but that is not their only appeal. Rather, quantum computers will bring the possibility to solve certain problems that cannot be solved by classical computers. There are many problems that can now only be solved by "brute force," that is, by painstakingly trying every conceivable possible solution and then checking the result for correctness.[3] Quantum computers—operating with quantum algorithms—will likely be able to solve certain problems in seconds what would take conventional computers months or years or even centuries to achieve.[4] Again, this is because quantum computers work in a fundamentally different way. The relevant application search then is for problems that present "quantum advantage," those applications that can benefit from the breakthrough, safe-cracking power of quantum computers.[5] Mathematicians can already teach us about the characteristics of certain problem types and suggest which of these will be favorable ground for quantum advantage. Lawyer-engineers will need to take the next step: match the identified mathematical characteristics of decisions amenable to quantum advantage to real-world legal concerns. Once we know what to look for, we may well find a plentitude of legal determinations that will profit from quantum computation.

The "law of the instrument" is a species of cognitive bias: If all you have is a hammer, everything looks like a nail. And this may prove true with respect to quantum computers. In the end, many promising applications will yield disappointment, as quantum computers will fail to outperform other tools that are simpler yet better suited to the task. Ordinarily tools are developed to respond to identified needs; yet in computing—from the Turing Machine (our idealized classical computers) to Richard Feynman's original speculation of the quantum computer—the conception of the "tool" preceded both physical embodiments (actual computers that work) and the identifications of applications. Yet our experience with modern technology strongly suggests

Image: Lan Zhang / iStock / Getty Images Plus that new tools—with novel and powerful capabilities—will lead to surprising applications. Even legal technology will participate in the search for "killer apps" that take advantage of the strange yet marvelous potential of quantum computing.

As the launch of quantum computers approaches, law is already undergoing a profound transformation driven by its interplay with new technologies. The practice of law is becoming more and more computational in its form and function. We now view much of law as expressions of algorithms; a simple program (think of TurboTax) can instantiate very complex legal rules. However, at this point we do not yet fully understand what quantum computing will offer the legal world. Quantum computers will require the discovery of quantum algorithms; the presence of pure computational capacity (even if of a different kind than that of conventional computers) gives us little guidance of the kinds of problems quantum computing can solve. The law is co-evolving with new computational technologies and data science (including big data); natural language processing and machine learning are currently being deployed to model law and to build tools capable of legal analysis and predicting legal outcomes.[6] Quantum computing will likely drive further developments in modeling and operationalizing law and facilitating legal prediction.

As noted earlier, quantum computing differs profoundly from classical computing. Classical computing involves the logical manipulation of bits—registers that at any moment during a computation contain the value of 0 or 1. Quantum computing uses registers known as qubits. Qubits contain an entire quantum state, which comprise vastly more information than the simple 0 or 1 values found in ordinary computer bits. A quantum state can be imagined as a cloud-like probability distribution—reflecting a "superpositioned" combination of both 0 and 1 values. The probability distribution of a particular quantum state encodes values over an entire range. Quantum computation involves manipulation of these quantum states, which can be thought of as a simultaneous calculation of all values, as opposed to a particular value.[7]

At the end of the computation, the output from the relevant qubit is not the processed manipulated quantum state. Rather, due to what quantum theorists describe as the collapse of the quantum state, it will read either as a 0 or a 1—exactly as is the case with the output of a classical computer. But a single quantum result carries little or no information by itself. Rather, quantum computation needs to run repeatedly—producing its mix of 0 or 1 outputs in some proportion. We can use this mix to generate the probability that either value is the "correct" output.

Quantum computation does not involve certainties; it involves probabilities—although at a sufficiently large scale there will be little or no discernible difference in the final outputs between quantum and conventional computers, two fundamentally different kinds of machines. The quantum way of thinking—with information coded in probabilities instead of certainties—will likely affect how we think of complex systems. It has long been understood that true equilibrium can be approached but never achieved in physical systems—and is likely even more so in social systems. Thinking about a system at once—without reliance on the individual case—and transforming it at once is likely to be liberating.

The law shares some of these characteristics as it is. The law can be thought of as a model representing the universe of cases—with an acknowledgment that not every case "fits" the model. Though we may not like it, we tolerate a degree of inconsistency, arbitrariness, and indeterminacy in the law. Perhaps it would ease our legal minds to accept that observations demonstrating that any outcome is possible need not mean that law is meaningless or unachievable!

Quantum logic, quantum algorithms, and quantum computing—together with our now well-established quantum understanding of the universe—can trigger quantum imaginings of law, opening up new possibilities for quantum rules, quantum adjudication, and quantum order.

QUANTUM LOGIC, QUANTUM ALGORITHMS, AND QUANTUM COMPUTING—TOGETHER THE LAW IS CO-EVOLVING WITH NEW COMPUTATIONAL TECHNOLOGIES AND DATA SCIENCE (INCLUDING BIG DATA); NATURAL LANGUAGE PROCESSING AND MACHINE LEARNING ARE CURRENTLY BEING DEPLOYED TO MODEL LAW AND TO BUILD TOOLS CAPABLE OF LEGAL ANALYSIS AND PREDICTING LEGAL OUTCOMES.

## QUANTUM IMAGINATION—ANTITRUST LAW

While we generally sense that quantum computing will have lasting effects on many areas of law, it is more difficult—at least at this point—to identify which fields these might be. Quantum computing will bring promise for better models of complex social relations; better tools for use by lawyers, judges, and regulators; and better legal and regulatory design.

Antitrust law is a likely field for early implementation of quantum computing methods. It is an area of law of immense innate complexity, involving challenging assessments involving economic, political, and social relationships and difficult trade-offs across competing values. Regulating markets is more difficult than regulating the actions of discrete legal persons. Antitrust is based on foundational laws, but it seeks to achieve broad economic goals, many of which are susceptible to measurement.

Defining the relevant market is a starting point for many types of antitrust analysis—and is a consistently challenging (and contested) exercise. Whether markets are defined broadly or narrowly often determines whether the scrutinized market behavior is legally acceptable or not.

Courts have proposed legal and economic tests to answer whether two products belong to the same market—based in large part on the degree of competition between them. That said, there are a number of other considerations that enter into the definition of a relevant market. As even a non-antitrust lawyer might imagine, there is sensitivity to the analytical purpose the market definition is intended to serve. As there are no bright lines, marking the bounds of a relevant market is not a pure technical exercise. It necessarily involves discretion and judgment, elements that exist in tension with our legal expectations of consistency and predictability. And we appreciate the fact that markets—however defined—are dynamic. There are firms that enter and exit, market shares that shift, and new technologies that create and destroy competitiveness between firms. We can point to the simple first-order antitrust question of what is the relevant market and see complexity and uncertainty everywhere we look.

Here then is a field open to quantum modeling. Among the strengths of quantum computing is solving complex optimization problems. Many legal tests appear to be optimization problems, where a judge is called on to "balance" two or more desired factors in making a determination. At this point, a judge is left to their devices in following the command of a particular balancing test, but quantum computing may bring more order—and more accuracy—to the process of taking multiple considerations into account.

A quantum computer—armed with appropriate programming—can "balance" multi-factors more adroitly than any judge. It can perform the optimization for any mix of inputs, determining the best suite of values. It could, for example, consider price elasticities (a dominant metric in market analysis), overlap of customer base, the mix of production technologies and product features, effects on input markets, and dynamic cost structures in assessing whether two products should be deemed to share a market.

Predatory pricing is another area of antitrust that could benefit from the power and insight of quantum computing. Predatory pricing—as conventionally understood—involves a firm with the financial resources underpricing its competitors' costs in a particular market and thus overtaking the market for itself. In recent years, there has emerged a great deal of skepticism as to whether predatory pricing (or its international equivalent, dumping) could ever be profitably practiced. The argument is that in classical markets, the resultant monopoly profits from "successful" predation would be insufficient to compensate for the losses sustained during the period of predation. Whether this is correct has largely been argued—in economics departments and in courts—as a matter of principle. But the problem is likely more complex—and involves interrelations of effects—than can be handled by a simple model. Quantum computing might enable demonstrations of the possibility or impossibility of predation in a particular case.

Antitrust *per se* rule cases could fall by the wayside, as quantum computers may lower the cost—and improve the reliability—of the balancing of consumer harms and benefits that fall under the alternative rule of reason. With quantum computers, every case could be examined under the rule of reason (although one imagines certain strong categories of anticompetitive behavior, such as price-fixing, would continue to be condemned, even with access to a potential rule-of-reason justification). With the use of quantum computing, judges would have access to better models that will be able to capture complex chains of cause-and-effect as certain counterfactual assumptions are run.

Optimizing consumer welfare—the manifest goal of American antitrust—can be more directly and more effectively operationalized through quantum computation. Importantly, quantum computing may lead the way to fuller internalization of dynamic effects, liberating antitrust theory from its classical, static models.

## QUANTUM IMAGINATION—BANK REGULATION

Financial regulation is one area where quantum computing capacities are currently being developed. Canada's D-Wave is currently selling a computer system that successfully emulates quantum processing through a method it calls "quantum annealing."[8] Researchers have used D-Wave's technology to improve the prediction of systemic bank failure,[9] a matter of great interest to financial regulators across the globe.

These studies suggest that quantum computers will be able to better signal when a single institutional failure will or will not trigger an out-of-control financial collapse. It may be possible to engineer an "early warning system" that will permit earlier and hence cheaper and more effective regulatory interventions than are now possible. A regulator might be able to avoid a more general financial system collapse by addressing shortcomings within particular institutions that comprise the system. Quantum models may permit a more sophisticated understanding of a financial system that will facilitate risk reduction that will translate into lower costs. Moreover, better models built on quantum computers may defer, delay, or avoid interventions that would now be acted on as "false positives," situations where regulatory action would now be undertaken (due to our current modeling limitations) but that do not justify those responses. A deeper, quantum-enabled understanding of financial meltdowns can assist in better distinguishing safe situations—avoiding unnecessary alarms—as well as alerting regulators to previously undetected systems of true danger.

Better modeling—of the kind now being explored by academic researchers using D-Wave's technology—should lead to better regulatory tools. These tools may be deployed both by bank supervisors and by risk management officials within the banks themselves. Better models of complex systems—like a national or international banking system—will also suggest new or more nuanced regulatory approaches. We can and do expect the law to change in response to our effective quantum-based understandings of these systems.

## IMPLICATIONS FOR LAW AND LAW PRACTICE

Powerful and cost-effective quantum computers will soon arrive—and that appears to be one of the few certainties in this area of technology. The existence of quantum computers—and their special capacities—will stimulate a search for all types of applications, including those for legal contexts. Quantum computing—and the accompanying familiarized quantum thinking—will undoubtedly change law and legal practice. Quantum computing will expand possibilities of modeling law, will introduce new regulatory forms, and will lead to more powerful tools for the legal profession. Many of these changes will take place "under the hood" and will not demand a thorough understanding of quantum theory, but the practitioner will experience a different feel from the technology. Legal information retrieval will bring back different—and more useful—results. Quantum computing may open up new methods for identifying and supporting legal arguments. The body of existing law will be more effectively accessed—for planning or for advocacy.

Quantum computing will stimulate profound substantive changes in certain fields, as it permits deeper understanding of complex phenomena and more powerful models. Antitrust and bank regulation are examples of fields where quantum computing can be expected to have an important impact.

And the introduction of quantum computing will raise ethical, legal, and distributive challenges.[10] Quantum computing may be devoted to antisocial uses and so will require specific regulation (quantum computers threaten most conventional cryptography, for example). There will likely develop a quantum computing "gap" between haves and have-nots, as certain nations, firms, or groups dominate access to quantum computers. Quantum computing, like the digital technologies that arose during the past thirty years, might also have the unfortunate effects of exacerbating wealth and power differentials in a manner that attracts criticism and resistance.

That said, quantum computing will have a stimulating effect on our minds, including our legal imagination. It will lead us to look for new approaches, new ways of thinking about problems and their solutions, new roles for law including quantum-inspired law. Today much of this is ill-defined, but the technology is now arriving, and its consequences will be felt by lawyers over the remainder of this century.

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## ENDNOTES

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