Introduction

Technological change is everywhere we look today, from the most advanced economies to the least advanced, and goes to the heart of individuals' hopes—and anxieties—about the future. It also poses a very difficult problem for central banks, because it is very hard to measure, yet it affects output, labour markets, wages and inflation. In short, technological change represents a source of deep uncertainty for policy-making in an already-uncertain world.

This paper is about managing technological progress in monetary policy-making. We look to three past industrial revolutions for insight. We then apply those lessons learned to the fourth industrial revolution—the emergence of artificial intelligence—and consider how central banks might manage the risks as they unfold. We find that there has been a steady evolution in monetary policy-making in the wake of past industrial revolutions. In particular, the main pitfalls that emerged during the early 2000s have led to the progressive incorporation of financial vulnerabilities into monetary policy risk management.

Anatomy of a technological advance

At the risk of oversimplification, predicting how the economy and especially inflation will evolve depends on an understanding of both demand and supply at the macroeconomic level. Aggregate demand—consumer spending, exports, business investment, government spending—interacts with aggregate supply—the capacity of the economy to generate goods and services—to determine the behaviour of inflation. This interaction is generally the focus of the central bank, which is often charged with keeping inflation low and stable. By manipulating interest rates, central banks can strengthen or weaken aggregate demand relative to aggregate supply, thereby affecting the path of inflation.

Economic models contain measures of risk wherever statistical data have been used to estimate a relationship. This would include the various components of aggregate demand and aggregate supply. When forecasting, these measures of risk are generally projected to converge to zero in the future. However, their historical variance can be used to derive statistical ranges around the model forecasts. Taking forecast ranges seriously in policy-making can lead to very different decisions than those that ignore forecast uncertainty altogether.

The focus of this paper is technological advances, which influence the economy's aggregate supply. The behaviour of aggregate supply is very complex, as it depends on the behaviour of a multitude of firms, their workers and technological developments. Technological advances are adopted continuously throughout the economy. Accompanied by growth in the labour force, this creates a trend line for the economy's potential output, which economists generally extrapolate into the future. But around that trend line are many data points on output that deviate from the line, creating a statistical distribution around potential output. That statistical distribution is amenable to measurement and can be treated as risk by the forecaster and recognized explicitly in forecast confidence intervals.

Every now and then, however, there is major leap in general-purpose technology, the consequences of which are simply not predictable or even measurable until some time after the fact. This is the sort of uncertainty that interests us here. Such uncertainty is sometimes referred to as "Knightian," in deference to Frank Knight (1921), who was the first to make this distinction between risk and uncertainty.

Incorporating Knightian uncertainty into monetary policy-making is obviously much more difficult than incorporating standard measures of risk. Conceptually, the technological advancement process is as follows. Suppose a new technology emerges that has application across a wide range of companies. We refer to this as a general-purpose technology. Electricity or computers are obvious historical examples. Early in the process of adoption, companies that introduce the new technology usually create excitement in stock markets as investors try to reap the big gains of early movers.

A firm that adopts the new technology can produce at a lower cost than other firms. Often this is because the firm can re-engineer its production process with fewer workers. In other words, workers are laid off because of the new technology. Competing firms must also adopt the new technology or they will be squeezed out of business. Those with the financial ability to make the investment do so; others do not. It is possible that a lot of jobs are eliminated in the process. Of course, the new technology has also created other jobs never dreamed of before, software engineers, for example. Employees in these new jobs enjoy strong incomes because of the widespread and growing demand for the new technology.

Competition between firms deploying the new technology results in falling prices, with the benefits of lower costs passed on to consumers. This can cause a generalized deflation under certain monetary regimes, such as the gold standard. Regardless, workers whose jobs are secure find themselves with more spending power than before. As a consequence, those workers buy more of everything, as do the workers who hold the brand-new jobs of creating, selling, supervising or maintaining the new technology. Accordingly, new jobs are created in traditional sectors of the economy, too. In effect, the new technology creates a rising tide that raises all boats, in time.

This sequence is best described by Schumpeter (1942) as a process of creative destruction. It is human nature to worry mainly about the destruction part of the story. Economic history is littered with tales of resistance to new technology because individuals could not imagine the final destination or what role they might play in it. In part, this is because that destination may be quite far off. Individuals are disrupted by the introduction of a new technology, and it may be a long time before they are able to find a new place in the labour market, if they ever do. Even so, history demonstrates that technological progress ultimately creates more jobs than it destroys, and the overall impact on economic growth warrants at least some of the optimism that tends to infect asset markets during such episodes.

The process of incorporating a new technology and finding a new macroeconomic equilibrium with full employment can also be complicated by secondary forces. For example, most technological leaps have generated excessive investor enthusiasm—speculative bubbles, in short—either because people underestimate the competitive forces that will limit the profitability of new technology companies, or because short-lived companies capitalize on the excitement but fail to survive. The collapse of a financial bubble can put a huge dent in business confidence and slow down the natural adoption of a new technology by other companies.

Furthermore, creators and early adopters of a new technology may be well-placed to reap the lion’s share of the benefits in the early going. This means that the economy sees the growth consequence of technological change in isolated pockets rather than seeing it spread everywhere. Harberger (1998) likens this to the growth of mushrooms, as opposed to yeast. This natural pattern of growth is clearly contentious, as Howitt (2015) argues, because it creates all kinds of winners and losers, and therefore distributional consequences. This makes technological change a matter for politics and public policy, since it poses issues around market concentration and anti-competitive behaviour. Eventually, however, when full general equilibrium is re-achieved, the second-round effects of mushroom-like growth will appear more like yeast, because they will affect all sectors where consumers spend. Without developing the idea further, we can summarize by saying that the adjustment process to a new technology is complex, may be long-lived and could be very difficult for many people.

Another key financial consideration concerns debt. Because the prices of many products may fall as a general-purpose technology spreads, the burden of debts incurred in the past will increase in real terms, particularly for firms that are not first-movers. This can prove to be a serious headwind, or even fatal, for companies trying to adapt to the new technology. Again, this can mean more layoffs of workers and a more disruptive near-term path for the macroeconomy. The pervasiveness of this effect will depend on the monetary regime that is in place, as we will see below.

The bottom line is that a new general-purpose technology will raise at least the level of potential output per person permanently and may very well raise the trend growth rate of the economy for a long time. However, the transition from the old economic growth trend line to the new trend line may be a highly disruptive one, where the economy slows, or even shrinks in level terms, before the new upward momentum emerges. As such, there is obviously a potential role for macro policies, both monetary and fiscal, in facilitating the transition due to technological change, even if that role is constrained by the uncertainty inherent in a technological shock to the economy. That uncertainty cannot be managed *ex ante*; rather, there needs to be a process of learning by policy-makers, consumers and firms alike, in real time.

Three industrial revolutions

We are at the earliest stages of the fourth industrial revolution, as coined by Klaus Schwab (2016) of the World Economic Forum. It is based on artificial intelligence and is likely to have profound implications for virtually all aspects of economic activity. It therefore represents perhaps the biggest challenge policy-makers have faced in a long time.

It is worth reviewing experiences in the first three industrial revolutions to help us better understand the fourth. There is an extensive literature on the first three industrial revolutions, with multiple views on cause and effect. I will not do justice to that literature here but will instead offer an interpretation of that broad sweep of history that is consistent with the stylized facts. The objective is to identify the commonalities across past industrial revolutions and draw lessons for monetary policy, using the generic narrative around technological advances set out in the previous section as a template.

The first industrial revolution, generally dated from the late 1700s until the late 1800s, was about the steam engine, which replaced human and animal energy. Although the process moved slowly, wide swaths of existing firms and jobs became irrelevant, particularly in the more established economies of Europe. The innovations fostered an extended period of booming stock prices, and then a financial collapse, centred in Vienna. Deflation in goods prices meant that outstanding debt burdens were rising in real terms, helping to foster banking crises. The world was operating on a gold standard, so the money supply could not be expanded unless more gold was discovered and produced. This meant that rising aggregate supply due to the new technology necessarily caused prices to fall. Today, we refer to the period of acute stress that accompanied the first industrial revolution, from 1873 to 1896, as the Victorian Depression.

The second industrial revolution ran from the late 1800s to the mid-1900s and was based on the combination of electrification and mass production. Firms scaled up and became vertically integrated, and production within those firms became highly specialized and organized along assembly lines. Once again, the world needed to absorb a significant increase in aggregate supply, and prices of a wide range of products fell. Accompanying this was a stock market bubble, the bursting of which paved the way for the Great Depression of the 1930s. The interaction of deflation with debt again prolonged the episode. Although the United States by that time had a central bank—and in 1935 the Bank of Canada would be created—the situation was poorly understood and macroeconomic policy did little to alleviate the downturn. However, it did foster considerable macroeconomic research, such as Keynes (1936), and there is little doubt that policy-makers learned a great deal from this episode.

The third industrial revolution dates from the mid-1970s, with its peak effect during the 1990s. It was based on the computer chip—electronics and information technology combined to allow production automation and coordination of business logistics at a distance. Firms were able to streamline processes to reduce labour input. They could also fragment their production processes to increase specialization by deploying global supply chains. As a result, firms became less vertically and more horizontally integrated. In effect, technological advances and the opening of new economies, especially in Asia, combined to make globalization feasible. Once again, the world needed to adjust to a significant increase in aggregate supply, and the adjustment took a long time. The excess capacity was concentrated in Asia, prompting a series of competitive devaluations around the region. The interaction between falling prices, exchange rate depreciations and indebtedness added to stresses for companies, households and fiscal authorities, particularly where there was a sizable debt burden denominated in a foreign currency. These were the ingredients that made the process contagious through many developing countries.

Even so, unlike the first two industrial revolutions, the third was not associated with a global depression. As with the others, it was associated with a stock market boom and collapse (the dot-com bubble and subsequent tech wreck), labour market disruption and low inflation. However, policy-makers clearly did a better job this time around. Indeed, one could take hope from the fact that the Great Depression was much shorter-lived than the Victorian Depression and the global adjustments to the third industrial revolution were faster still, because monetary and fiscal policies (including social safety nets) have improved over time. Unlike the first two industrial revolutions, the third was accompanied by an extended period of easy monetary conditions because many countries had made controlling inflation a centrepiece of monetary policy in the 1990s. This allowed the new technology-led growth to unfold without causing a major slowdown or generalized deflation. As the technology shock matured, however, and monetary conditions remained easy, an unanticipated side-effect emerged: financial imbalances built up, leading to the global financial crisis and the Great Recession. As a result, regulatory and monetary policy frameworks were adjusted to mitigate such risks in the future. Again, policy-makers are learning from past mistakes.

This broad-brush summary of three complex historical episodes demonstrates some key commonalities around major technological advances discussed earlier. Workers are displaced, stock markets boom, brand-new jobs are created, prices and inflation fall, debt burdens rise and can provoke crises, and stock markets crash. The overall rise in prosperity eventually creates a wide range of job opportunities for displaced workers, although the passage of time may mean that some are permanently detached from the workforce. The summary also highlights the evolution of macroeconomic and regulatory policies through history, from non-existent to passive, to active, to active plus the addition of new tools, collectively called macroprudential policies.

The fourth industrial revolution and monetary policy

The fourth industrial revolution is about the digitalization of the global economy. At its heart is machine learning, big data and artificial intelligence (AI), which have the potential to improve all areas of economic activity. The same fear that confronted individuals during the first three industrial revolutions is widely apparent. Occupations at risk include manufacturers, truck drivers, medical diagnosticians, operators of agricultural machinery, financial advisers and workers in call centres.

Experience with the first three industrial revolutions suggests that we can expect to see a significant disruption of workers, a shift upward in potential output growth and a prolonged period of low inflation or deflation as the productivity effects of AI work their way through our economy. This would of course mark a significant departure from recent experience, which has been characterized by downgrades in global potential output growth, for reasons related to both demographics and productivity, as well as the maturation of China's growth process. Indeed, the US–China trade war is also likely to weigh on global potential output growth. No doubt, this backdrop will make many skeptical that a surge in productivity is underway due to AI, particularly if the statisticians have difficulty in capturing it, as happened during the third industrial revolution. This is exactly why it is important to characterize the situation as highly uncertain, rather than as a well-recognized positive supply shock.

Policy-makers have adapted their tools in light of experience during the previous three industrial revolutions. The lessons learned from the third one, in particular, point to the need to allow the supply-led economic expansion to run with accommodative monetary policies, using inflation targets to anchor monetary policy, while deploying macroprudential tools to guard against the buildup of imbalances in the financial system.

This general description of optimal monetary policy in the face of a major technological advance is clearly an oversimplification. It would probably not pass the scrutiny of either law makers, financial markets or the general public. Nor does it acknowledge the significant uncertainties that central banks will face in real time. Assertions that the economy is picking up speed due to a technology-led positive supply shock that will prove to be disinflationary so that interest rates can hold steady, or even decline, will be impossible to prove until long after the fact. There are three reasons for this. First, even though everyone knows that a technological advance is underway, it is not possible to predict its spread or the rate of accumulation of the productivity benefits. At a macro level, the data will still contain companies that are not adopting the new technology and will therefore hold measured aggregate productivity back. Second, statisticians will find it difficult to track the "new economy" using traditional economic measures. And third, the economy will still be subject to many other shocks, as it always is, which will add to the confusion in standard economic signals. The situation is bound to attract considerable debate, during which the credibility of central banks will be tested.

Given the obvious similarities with what we may face in the near future, it is worth examining the conduct of monetary policy during the third industrial revolution in more detail. In particular, key to understanding how policy is being made at a point in time is to understand how the central bank was forecasting the economy and inflation. In general terms, economic forecasters would have been most uncertain about how the economy's aggregate supply was evolving. The way this uncertainty would manifest itself is as follows. The forecast of aggregate demand would be based on existing relationships between employment, incomes, spending and so on; aggregate supply would be a trend line based on average recent economic performance, built up from trend productivity and the evolution of the labour force. The adoption of new technology would cause economic growth to be stronger than expected, but because that growth would be coming from new capacity, supply would lead demand, and inflation would tend to be slower than forecast. This would be accompanied by a mixed labour market performance, with job losses in affected sectors and gains in the technology sector.

These characteristics summarize the latter half of the Greenspan era from 1987–2006—a jobless recovery from the 1990–92 downturn, but solid growth and lower-than-expected inflation. We also experienced stock market frenzies and collapses, especially around tech and dot-com companies. Because of globalization, much of the cost compression was in firms in emerging-market economies, especially in Asia. This interacted with high debt levels, much of which was denominated in US dollars, leading to the sequence of crises in Asia and later in Russia. But in the United States, the consequences were modest at a macro level—the economy kept growing and inflation pressures remained muted, while monetary policy remained accommodative. This hid an important disruption to the labour market that reverberates today.

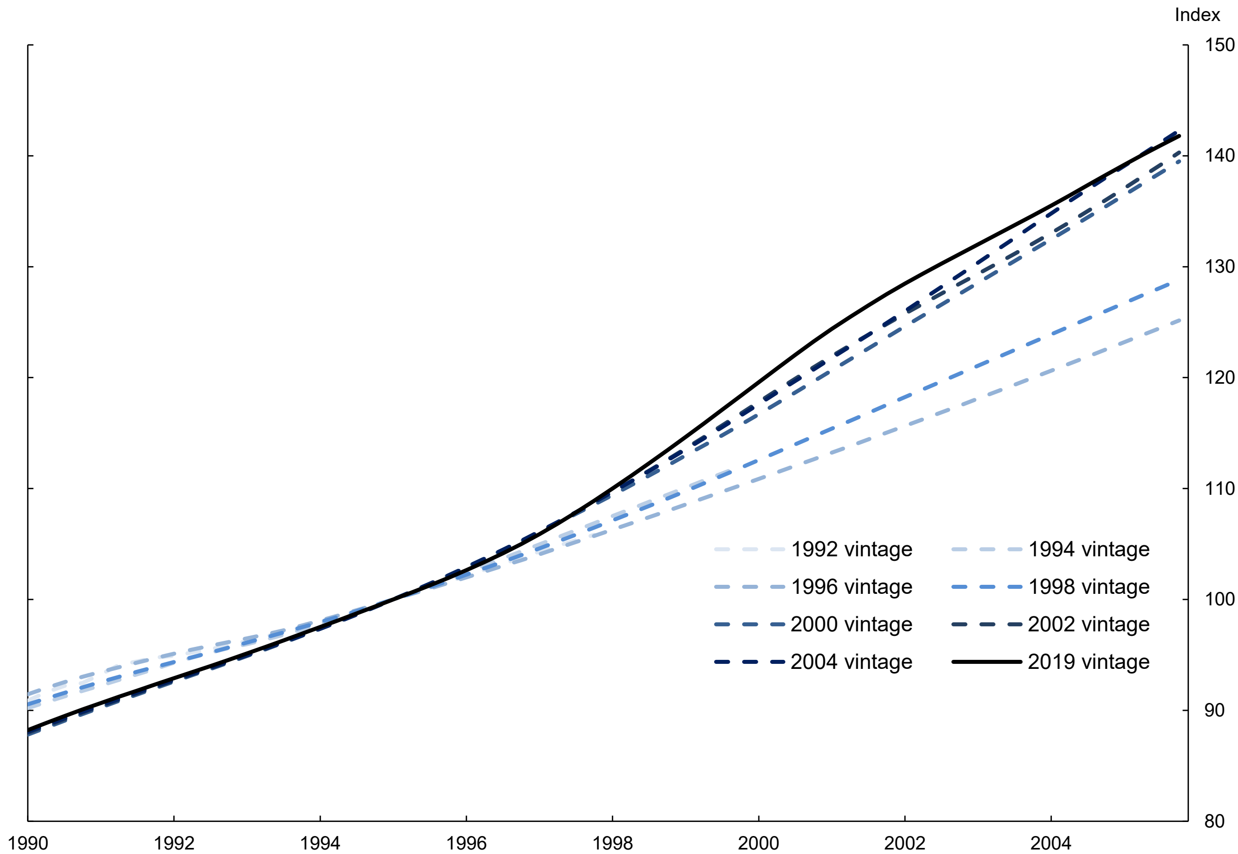
Through this time, US monetary policy was managing elevated uncertainty (see Powell 2018). In retrospect, the level of uncertainty around aggregate supply was unprecedented. As it turns out, using inflation as an anchor for policy was fortuitous. Since the technological shock led to a series of negative inflation surprises, monetary policy was able to accommodate the additional growth in the economy. This provided for stronger growth overall, making the transition to a new technology much easier than was observed through the previous two industrial revolutions under the gold standard.

It is worth working through this experience to try to replicate the real-time observations that economists were making at the time. A popular means of estimating aggregate supply is to use a filter on actual gross domestic product (GDP) data to capture the underlying supply performance of the economy. Such a method will be late in capturing a shift in aggregate supply behaviour, but it is always going to catch it eventually, in either direction. The method may be supplemented with judgment based on bottom-up estimates of capacity through detailed analysis of labour market trends.

Chart 1 illustrates the real-time problem faced by the Federal Reserve under Chair Alan Greenspan in the 1995–2005 period. With the benefit of hindsight, we now know there was a significant positive supply shock to the US economy that began around 1995. By 2005 this supply shock had driven cumulative growth more than 10 percent higher relative to the projections that were made around 1995. However, it was not until around 2000 that the materiality of the shock started to be realized, as forecasters repeatedly underestimated GDP growth. Greenspan (2000) noted that "most of the gains in the levels and growth rate of productivity in the United States since 1995 appear to have been structural, largely driven by irreversible advances in technology and its application." The implication is that the Fed was quite wrong about where US potential output actually was in the mid- and late 1990s, and it still had some learning to do even in the early 2000s. Medium-run potential output growth was being underestimated by margins ranging from about 0.75 to 1.75 percent per year, with an average of about 1.25 percent.

Chart 1: Real-time vs. ex-post estimates of US potential output, 1990–2005

Real potential output, index: 1995 = 100, quarterly data



Sources: Congressional Budget Office (CBO) and Bank of Canada calculations

Last observation: 2005Q4

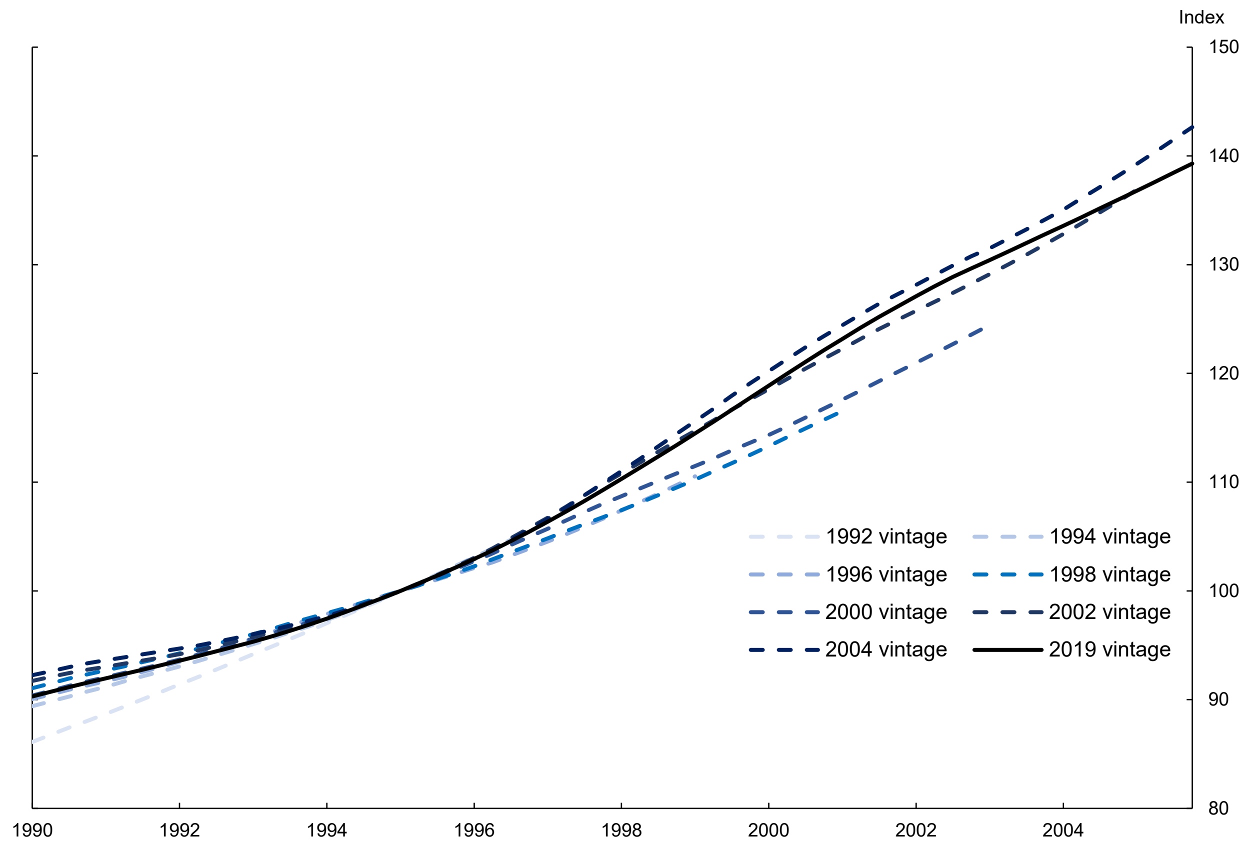
Note: The dashed lines are vintages representing the CBO's real-time estimates of US potential output based on the data available in January of a given year, while the solid line represents the CBO's estimates as of August 2019.

Chart 2 repeats this exercise for Canada, using historical data on Bank of Canada forecasts constructed by Champagne, Poulin-Bellisle and Sekkel (2018), with similar results. The cumulative supply shock was somewhat smaller in Canada than in the United States, but the implications for monetary policy-making were essentially the same. Through the period in question, we now know that productivity growth was unusually rapid, but the statisticians took some time to catch up to that new trend.

In practice, of course, few central banks take a mechanical approach to their policy formulation, because they know well that to do so would be to expose themselves to a wide range of possible forecast errors, potential output being only one. Rather, as Powell (2018) argues, the Fed during the Greenspan era could observe that inflation was lagging what its models were predicting, so it entered each policy window with a bias to inaction.

Chart 2: Real-time vs. ex-post estimates of Canadian potential output, 1990–2005

Real potential output, index: 1995 = 100, quarterly data



Source: Bank of Canada and staff calculations

Last observation: 2005 Q4

Note: The dashed lines are vintages representing staff's real-time estimates of Canadian potential output based on the data available in the first quarter of a given year, while the solid line represents the staff's estimates as of April 2019.

Today, we seem to be facing a very similar situation. Inflation has been underperforming expectations in many economies for several years, both advanced and emerging-market, in all regions of the world, given the growth in the economy and the performance of labour markets. This has given rise to a lot of research around questions such as these:

1. Have Phillips curves flattened or perhaps disappeared altogether?
2. Has the inflation process gone global due to globalization?
3. Has successful inflation targeting anchored inflation expectations so well that inflation is stuck?
4. Have we entered a period of secular stagnation, in which case equilibrium real interest rates are far lower, and monetary policy consequently far less stimulative, than we realize?

After considerable research, not much of a consensus has emerged on these questions, although there is some empirical support for all of them. But given the evidence accumulating daily of the effects of the introduction of AI into the economy, perhaps we should be focusing more on a different question:

5. Could it be that a profound positive technology shock is supporting economic growth, holding back wage growth and inflation, and redistributing resources from the goods sector to the service sector?

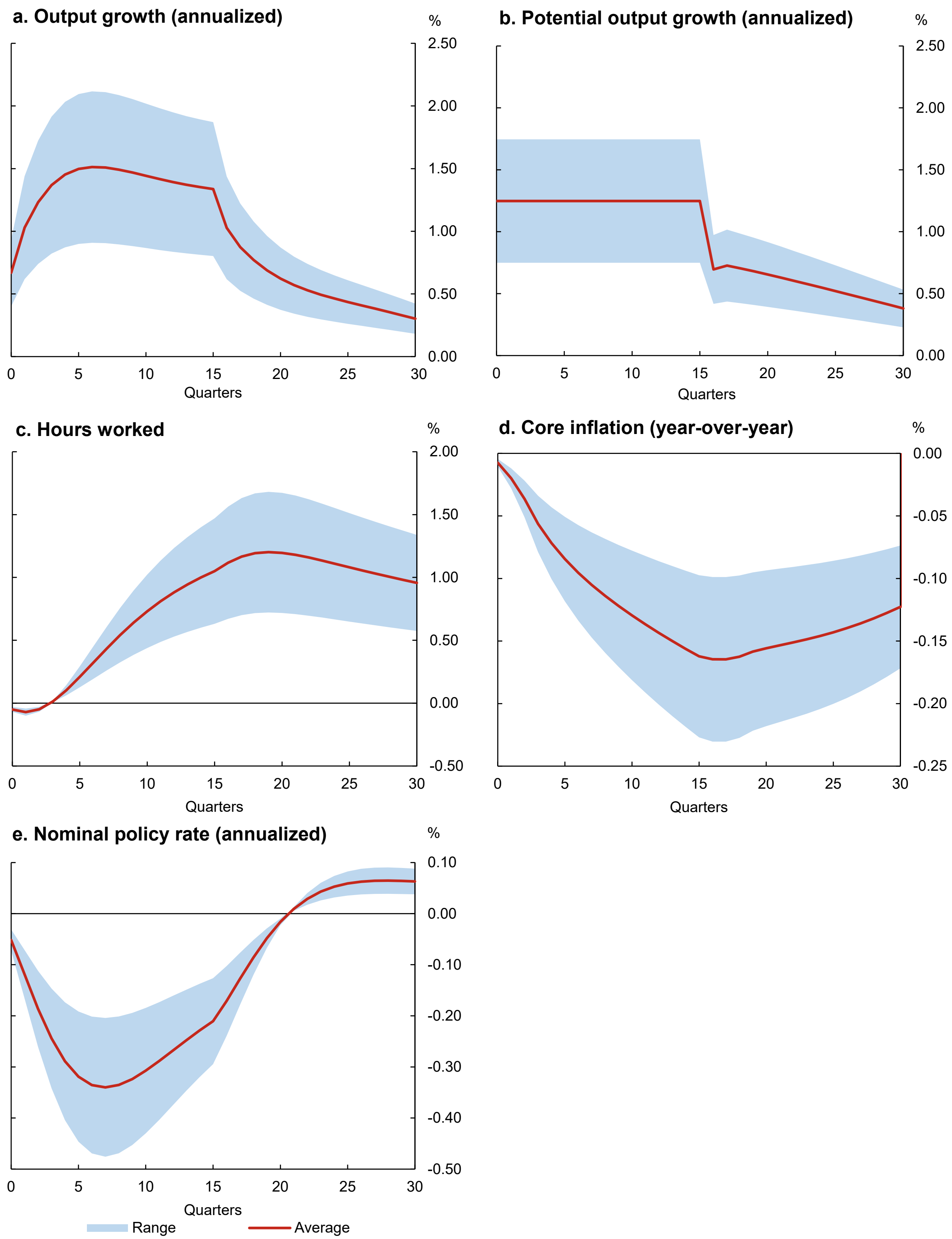
In astrophysics there also are many unanswered questions, and a single theory, widely tested but not actually observed—the existence of dark matter—helps explain many of them. Perhaps in macroeconomics, a difficult-to-prove positive supply shock will one day help us backcast the economy with much more accuracy than we can forecast it today.

Today's statistics so far offer little by way of support for this hypothesis, just like in the late-1990s. Of course, we are open to the development of tools that can help us discover new evidence of supply growth. The textual analysis approach employed by Alexopolous (2011) shows promise in this regard. Meanwhile, though, productivity growth has remained relatively slow, despite much anecdotal evidence that AI is being deployed in various parts of the economy. At the same time, investment in intangibles is rising as a share of total investment, making it much harder to estimate the economy's capital stock. Firms are offloading many functions to the cloud and paying for them as regular expenditure items, thereby depressing measured investment spending. Some firms have large numbers of IT specialists on the payroll who develop applications and customized services for clients, activity that amounts to investment but is actually treated as an expense line item. Statistics Canada (2019) estimates that investment in data, databases and data science was in a range of $29 billion to $40 billion in 2018, or on the order of 1.5–2.0 percent of GDP, concluding that "the statistical system has some catching up to do."

Fortunately, the experience during the Greenspan era provides a case study for managing the risks associated with the positive technology shock hypothesis, as well as guidance as to the pitfalls associated with it. Greenspan's approach was to hold interest rates despite a very strong economy because he believed that a positive technology shock was holding back inflation. Edge, Laubach and Williams (2007) have studied this issue in detail. They suggest that understanding of a productivity shock can be held back by data revisions and the signal extraction problem faced by agents trying to determine whether shock realizations are permanent or temporary. The paper shows how slowly professional forecasters revised their estimates.

We have replicated such a situation using the Bank of Canada's main structural model, the Terms-of-Trade Economic Model (ToTEM) (see Dorich et al. 2013). We subjected the model to a four-year episode during which repeated productivity-growth shocks drive potential output significantly above initial expectations. The simulation results are summarized in Chart 3. The red lines correspond to a situation where shocks have been calibrated to increase medium-run potential output growth by 1.25 percent, as in 1995–2000, while the blue bands cover all outcomes associated with a shock range of 0.75–1.75 percent. All results have been reported in deviations from the economy's pre-shock path. We assume that the neutral rate of interest remains unchanged throughout the shock, although in a more general analysis it would probably be drifting upward in the background.

Chart 3: Macroeconomic implications of a real-time positive technology shock in ToTEM



Source: Bank of Canada calculations

Under this shock, the real side of the economy experiences a significant expansion while the effect of new technology on marginal costs simultaneously leads to sustained downward pressure on inflation relative to target. Given the relatively high weight that ToTEM's historical Taylor rule places on stabilizing inflation, these competing considerations call for an extended period of monetary easing. Obviously, were the central bank to hold rates unchanged instead, the surge in economic growth would be pared back somewhat, but inflation would fall even more below target. Nevertheless, as modelled, inflation would remain within a 1–3 percent target range under either policy scenario. This is an important subtlety. Given that deflation arises only in certain sectors of the economy, it is worth asking whether the central bank should be working to maintain average inflation, thereby boosting inflation in other sectors, rather than just letting the disinflation from new technology make its way through the system. Considerations would include the magnitude of the inflation shortfall and how that might cause inflation expectations to edge lower.

Furthermore, financial vulnerabilities were building during the early 2000s in the US economy and elsewhere as a result of the prolonged period of low and steady interest rates, along with lax regulatory oversight, sowing the seeds of the global financial crisis. Cutting interest rates even further in the face of the technology shock, as the Taylor rule in our model advocates, likely would have caused those vulnerabilities to grow even more. This is not necessarily the case because faster real economic growth mitigates financial vulnerabilities on the margin, even as lower interest rates cause vulnerabilities to increase. Accordingly, the situation calls for close monitoring of financial vulnerabilities.

Meanwhile, the institutional setting has changed radically since the Greenspan era. The Basel III reforms, the creation of the Financial Stability Board reporting to the G20 and the implementation of a wide range of macroprudential measures in many countries all mitigate such financial stability risks in the future. Most central banks now invest a great deal in monitoring financial vulnerabilities. For example, the Bank of Canada has a large Financial Stability Department, an annual *Financial System Review*, and a Financial System Hub on its website that is the repository for a continuous flow of data, analysis and new research.

Furthermore, central banks have been working for some time to integrate financial stability risks into their standard inflation-targeting frameworks (see, for example, Poloz 2014). Presently, the Bank uses a "growth at risk" (GAR) framework to this end (see Adrian, Boyarchenko and Giannone 2019; Ueberfeldt and Duprey 2018). In this framework, choosing a rate path to minimize the departure of inflation from target minimizes "macroeconomic risks" to economic growth, but also has explicit consequences for "financial stability risks" to economic growth. In effect, rising financial vulnerabilities cause the downside tail risks to the economic outlook to increase in scope and probability. In certain conditions, policy-makers face a trade-off between the two classes of risks when choosing their path for interest rates and can use the concept of "growth at risk" to quantify the trade-off and help inform their choices. For example, if macroeconomic risks point to a lower interest rate path, but financial vulnerabilities are high, that lower rate path can cause financial stability risk to rise to unacceptable levels. In other situations—when inflation seems likely to move above target and financial vulnerabilities are high—the contemplated rate path can reduce both sets of risks at the same time.

Notice that taking financial vulnerabilities into account does not mean setting the inflation target aside. However, it may mean adjusting the horizon over which inflation is moved back to target after a shock has caused a deviation. Also, the trade-offs are based on a given macroprudential setting. Indeed, changing the parameters of the underlying macro model, changing the model that captures the dynamics of financial vulnerabilities, or changing the macroprudential setting will alter the risk trade-offs faced by the central bank. The Bank's GAR framework remains a work in progress—presently it is based on a VAR model of the economy, but future work will twin GAR with a full structural model with properties like those of ToTEM. However, the GAR framework is informing monetary policy deliberations already. Such a framework is especially useful when financial vulnerabilities are already high, which is clearly the case in Canada's household sector. In such a context, putting future economic growth at risk by allowing financial vulnerabilities to build through lower interest rates, in order to prevent inflation from easing temporarily by less than 1 percent, may prove to be an unacceptable trade-off.

Accordingly, a more fulsome risk management framework can put important nuance on Taylor-type rules. Essentially, it will mean putting a weight on financial vulnerabilities within the Taylor rule, as suggested by Adrian and Duarte (2018). Indeed, when uncertainty is taken seriously in monetary policy formulation, it can lead to asymmetric policy responses, as argued in Wilkins (2018) and Mendes, Murchison and Wilkins (2017)—aggressive responses to shocks in some situations, such as when we are near the effective lower bound, and cautious policy responses in others. These nuances, or departures from the usual policy rule or "reaction function," will of course attract close scrutiny by market participants. This is a strong argument for an integrated communications strategy to explain the risk management approach to decision making clearly, thereby maintaining policy credibility and well-anchored inflation expectations (Kozicki and Vardy 2017).

Conclusion

Central banks face considerable uncertainty today. Although we are understandably focused on the consequences of rising geopolitical risk and the potential consequences of a global trade war, we should not forget that other longer-term structural forces remain at play.

In particular, the fourth industrial revolution is underway. A review of the first three industrial revolutions points to macroeconomic features shared by such episodes, including creative destruction, financial excesses, lower prices or inflation and mismeasured productivity growth. The Greenspan era from 1986–2006, particularly 1995–2006, represents a case study. It took nearly five years of such symptoms before forecasters began to take into account the positive technology shock affecting the economy and potential output in particular.

There is a good possibility that we will experience something very similar over the next decade, as the fourth industrial revolution unfolds. The situation may be complicated by a trade war and the associated deglobalization, which may offset some of the revolution's positive effects. However, setting aside that complication, the prescription for monetary policy over the longer term is likely to be very much like that of the Greenspan era. While inflation remains subdued, we should allow growth to run, for this is a good way of providing upside potential to those negatively affected by new technology. Meanwhile, however, we will need to monitor carefully developments in the financial stability space. In the limit, we need to develop better frameworks to synthesize macroeconomic and financial stability risks and to capture the effects of macroprudential policies in our risk management problem. This will mean adding nuance to Taylor-type policy rules—not in the sense of assuming even more knowledge on the part of policy-makers, but less.

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