"Its computers stupid!" The spread of computers and the changing roles of theoretical and applied economics

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“It’s computers, stupid!” The spread of computers and the changing roles of theoretical and applied economics[1]

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Abstract

This paper challenges the widely held notion that the developments in computing are sufficient to explain the recent turn to applied economics. Developments in computer hardware were undoubtedly necessary, and they were sufficient to ensure that there were significant changes in economists’ practices, but to explain how and why economics changed, other factors need to be considered. It conjectures that the most profound effect of the increased availability of computers may have been to challenge the boundary between theory and applied work.

Keywords: Computers, Information technology, Economics, Econometrics, Applied economics, Software, Simulation.

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1. The problem

Economists generally explain the turn towards applied economics that has taken place in the past thirty to forty years by saying that it is the result of better data and more powerful computers. For instance, Justin Wolfers and Betsey Stevenson 2012 state that "computing power has made it extremely easy and cheap to analyse all the data you produce. An economist with a laptop can, in a matter of seconds, do the kind of number crunching it used to take a roomful of Ph.D.'s weeks to achieve. Just a few decades ago, economists used punch cards to program data analysis for their empirical studies. The result has been a boom in empirical research." Likewise, Justin Fox noted, in a recent column, that "one cause seems pretty clear. The biggest shift toward empirical work occurred between 1983 and 1993, and it was between 1983 and 1993 that personal computers became commonplace."[2]

Indeed, the consequences of computers for economics have been dramatic. They opened the door to the implementation of techniques which for years had been no more than a dream: bigger matrices could be solved, therefore more complex models could be analyzed; Monte Carlo simulations became possible, as were statistical techniques such as Multinomial Probit models, Full Information Maximum Likelihood estimation; and many others. They also produced a radical transformation in the working practices of economists: in the 1970s, computation using hand or desk calculators gave way to writing computer code, card

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suggestions.

[2] http://www.bloombergview.com/articles/2012-08-06/business-is-booming-in-empirical-economics and http://www.bloombergview.com/articles/2016-01-06/how-economics-went-from-theory-to-data

punching and data input, waiting hours for mainframe computers to execute programs, then reading rolls of paper containing the output and often plotting results by hand. Today all of this can be done using the keyboard and mouse of a computer featuring a graphical user interface. It is possibly because the effect of computers appears so obvious, that there are few historical works documenting the nature and extent of such influence, and those works that do exist focus on the use of computers for the estimation and testing of econometric relations (see Renfro 2011 and references therein)

The claim that "it's all computers" suggests that economists knew what they wanted to do but yet were held back by a lack of computing power. The history of economics is thus riven with economists' statements about how the advent of new technology would enable them to solve long-standing problems. For example, in 1948, Leontief thought the ENIAC could soon "tell you what kind and amount of public works were needed to pump-prime your way out of a depression," and in 1962, Daniel Suit wrote that with the aid of the IBM 1620, "we can use models of indefinite size, limited only by the available data" (cited in Halsmayer 2016 and Renfro 2003 respectively). In 1971, Rand's analysts Charles Wolf and John Enns explained that computers had provided a "bridge" between "formal theory" and "databases." In the late 1980s, Jerome Friedman (1989) believed statisticians had the ability to compensate for unverifiable assumptions. In practice, however, the relationship has been much more complex. It shows no correlation between the level of computational intensity of a modeling approach and its rise in the prestige hierarchy of the discipline since the 1970s. Two of the most computationally demanding approaches in 1960s and 1970s were computational (or applied) general equilibrium (CGE/AGE) and large-scale Keynesian macro-econometric modeling, and yet, just as improvements in hardware made it possible to remove some of the simplifications and approximation that constraints on computing power had previously dictated, enthusiasm for these approaches waned. The eventual outcome of the methodological battles of the 1970s and 1980s concerning econometric techniques, identification strategies and meaningful tests was the rise of quasi-experimental techniques, which were much less computationally intensive techniques than many of the methods used earlier.[3]

A second problem with the“it's-all-computers” trope is that it presumes that computerization is more important for applied work than for theory; yet computerization had the potential to transform theory as well as applied work, as it did in the natural sciences. For example, biologists used computer simulations to show how something as complex as an eye could have been the result of a gradual evolutionary process (see Dawkins 1996, chapter 5). If this has not happened in economics, or if economists and computer scientists have begun to come together only in the past decade, as suggested by recent papers and special issues of journals (see Blume et al. 2015) it is important to ask why it evolved in this way. The common response also avoids questions of how the rise of computing may be connected to changes in the way theoretical and applied work are conceived. For example, simulations could be considered to be either theoretical or applied, or neither, depending on the nature of the work done and on how theory and application are conceived. There is the possibility that classifying certain types of computer-intensive work (for example simulations) as “applied” may reflect a conception of economic theory that has been called into question by the emergence of new research practices.

[3] Computers were nevertheless important to the success of such methods because of they made it possible to collect, store and manage large quantities of data.

This paper tackles the question of how we might begin to think about these developments in the context of the broader changes in economics with which this volume is concerned. It starts by outlining a chronology for the spread of computerization within economics. This is essential, because the path to computerization was neither linear nor uni-dimensional: there were sudden "leaps" in hardware performance, software production, and the evolution of practices; and increased computing power has involved not just advances in processing power but also innovations in data storage and retrieval, networking and visual displays. It then uses a list of the functions of computing as the basis for some arguments about the implications of computerization for the transformation of economics that has taken place in recent decades, and to analyze how the computer transformed the relationship between theory and application, or failed to do so.

The evidence required to write a comprehensive history of the role of computing in economics is often hard to locate, with the result that our account is far from complete. We want to fill an important gap in the history of applied economics and to convince historians that careful attention needs to be paid to the role of the computer in their stories. However, we also want to persuade economists that a thorough account of how computers changed economics (and of how, sometimes, they failed to change economics) requires more testimonies and reminiscences from those who lived through the events that we discuss. Publications such as the *Journal of Economic Measurement* have strived to record economists' reminiscences of their computation and technical practices but much of the material needed for a more comprehensive history remains buried in economists' minds, never having made it into print.

2. Chronology

1940s-1950s the quest for faster calculating machines

In 1946, the first general-purpose computer, the Electronic Numerical Integrator and Computer (ENIAC) became operational. In the next two years, John von Neumann and others wrote stored programs and ran Monte Carlo simulations in the course of modeling nuclear fission. However, economists' interest in computing had come earlier. At Harvard, Wassily Leontief had used a mechanical computer at the start of his input-output project in the mid-1930s, and by the mid 1940s, working together with the Bureau of Labor Statistics, he was using an electro-mechanical computer, the Harvard Mark II, to invert a 39x39 matrix.[4] Though this worked, to an accuracy that exceeded what von Neumann estimated was possible, it was a slow process, taking six weeks and baskets full of punched paper tape. During the Second World War, Guy Orcutt, then a graduate student at the University of Michigan, designed and built two "analogue electrical-mechanical" devices that could solve problems in duopoly and spatial economics (Watts 1991: 172). During the 1940s and early 1950s, electrical analog computers developed rapidly and were used on a significant scale for simulation. Part of Orcutt's doctoral thesis involved designing a "regression analyzer" that could estimate regression and correlation coefficients (Orcutt 1948). This machine was built after he was appointed to a position at MIT and it was used to study, amongst other things,

[4] http://herbmitchell.info/Chap7a.htm (accessed March 1, 2016). Discussion of Leontief draws on Halsmayer (2016).

autocorrelated processes using Monte Carlo simulations (Orcutt and James 1948; Orcutt and Cochrane 1949). At the London School of Economics, Walter Newlyn and Bill Phillips worked on an hydromechanical analog computer. In 1949, they came up with the MONIAC (Monetary National Income Analog Computer). This was sold as a teaching aid depicting the circular flow of income and is often taken to illustrate a naïve "hydraulic" Keyesianism. However, because it models the relationships between stocks and flows, with physical flows of water ensuring that these are modeled properly (for otherwise tanks will overflow) it was capable of analyzing complex relationships (see Vines 2000: 48-9).

The years around 1950 produced great advances in econometric theory, with the development, at Cowles and elsewhere, of estimation methods and tests for goodness of fit. However, though computers existed, most economists had to rely on desktop calculators, which made meant that the spread of these computationally demanding techniques was slow (see for instance Durbin in Phillips 1988). A significant development in 1954 was the shift in estimating the Klein-Goldberger model, one of the earliest models of the United States economy, from desk calculators to a computer (Renfro 2004: 23). However, even then the shift was only partial, for in order to keep the task manageable and to check for accuracy, the computer was used to calculate certain moments with other tasks being performed manually. A significant issue was the accuracy of large calculations, which led to problems being linearized and broken down into sub-problems that could be solved reliably. Overall, the 1950s can be pictured as a race between the increase in the computational power of mainframe computers and the creativity of researchers. Reflecting on the installation of an IBM 650 at Iowa State University in 1956, Raymond Beneke (1994,15) explained that, in 1959, as soon as it was upgraded to accommodate 198 rows, linear programming became a tool that economists could apply to a wide range of problems and multiple regression analysis became almost a free good in comparison with the previous situation. However, despite this, the pressure to improve computational capacity remained as economists expanded the range of problems they sought to tackle.

In the 1950s computers were used not only for data analysis but also for what might be conceived as theoretical investigations (and in some of this work, as explained in Section 3, the distinction between theory and application became very blurred). Herbert Simon and Allen Newell wrote the program “logic theorist”, implemented on the Johniac computer recently installed at RAND, which used symbolic manipulation to prove mathematical theorems—the beginnings of artificial intelligence (Dick 2015). In the Sloan School at MIT, Jay Forrester (1958) used an IBM 704 computer to simulate the effects of a ten per cent increase in retail sales in a dynamic system involving production, sales and inventory accumulation. An IBM computer (IBM 560) was also used by Irma and Frank Adelman to simulate the dynamic properties of the Klein-Goldberger model, an activity that arguably blurred the boundaries between empirical and theoretical research (Adelman and Adelman 1959; Adelman undated). They were using an empirical model but were drawing conclusions about the ability of alternative theoretical models to generate lifelike data.

Harnessing mainframe computers: programming, data management, and new modeling possibilities (1960s-1970s)

From the 1960s mainframe computers were used more widely not just because of falling prices but because of technical advances that made them more reliable.[5] As economists' access to computers increased, they began to write the software needed to perform statistical calculations, a development that was as important as advances in hardware. This software development was not something external to the developments in economics but reflected economists' views on how research should be undertaken. At LSE, Dennis Sargan wrote Autocode for the Atlas computer, and the many additions by Evan Durbin, Michael Wickens and David Hendry exemplified LSE economists' concern with tests for model specification. The development of GIVE (General Instrumental Variables Estimation) by Hendry in the late 1970s reflected the influence of general-to-specific methodology. At MIT and then Berkeley, Robert Hall, aided by Ray Fair, Robert Gordon, Charles Bischoff and Richard Sutch, developed TSP (Time Series Processor), while Ed Kuh and Mark Eisner worked on TROLL. Throughout the 1960s, the focus was on parameter estimation rather than on the human interface or data management.

This focus on estimation began to change in the 1970s when data production and management became a primary concern for government and business. The Economic Council of Canada, which hosted Daniel McCracken's DATABANK system, became a model for the US after the Ruggles Committee, the Dunn report and the Kaysen task force all recommended the establishment of Federal economic data centers in the late 1960s.[6] This in turn led coders to build data management systems into software and scientific projects. The

[5] For example, MIT, the Department of Economics and the business school purchased an IBM1620, and at the Cambridge (UK) Department of Applied Economics, the ESDAC2 was replaced by a Titan computer.

many macroeconometric models developed during the 1950s and 1960s—Brookings, MIT-Fed-Penn, Saint Louis, Data Resources Incorporated (DRI), Office of Business Economics (OBE) Wharton—had become operational and their forecasts, and associated database and time-sharing computing services were commercialized by firms including Otto Eckstein's Data Resources Inc., Michael Evans's Chase Econometrics and Klein's Wharton Econometric Forecasting. The software developed by economists affiliated with these practices, such as DRI's EPS software, or Chase's XSIM displayed greater concerns with data management and ease of use. The development of panel data projects, such as the *Panel Survey on Income Dynamics* and the *National Income Longitudinal Survey* fostered the spread of applied microeconomics techniques, such as fiscal microsimulations (Sutherland 1999).

Cheaper and more reliable computers did not merely result in the more widespread application of existing econometric techniques. They also supported new modeling strategies. The simulation techniques separately introduced by Forrester and Orcutt at MIT were further explored by their founders, yet met growing resistance in some fields.[7] For instance, the use of dynamic systems simulation to show that the western model of economic growth was unsustainable in the *Limits to Growth* report of the Meadows Committee, published 1972, created a stir. Simulation models were accused of being too sensitive to *ad hoc* parameters specifications. Two years later, political scientist Howard Alker (1974) argued that computer simulation should considered "inelegant mathematics and worse social science." Other simulation models, based on Von Neumann's theory of automata were also investigated. In

[6] See Privacy and Efficient Government: proposals for a National Data Center, *Harvard Law Review* 82(2), 400-417.

1969, Thomas Schelling presented a dynamic model of segregation in which the interactions of agents according to a set of rules produced spatial clustering. Several computer simulations of his model were produced in the next decades. The development of computational general equilibrium by John Shoven and John Walley likewise represented in break in the traditional theoretical approach to general equilibrium models (Ballard and Johnson, this volume). Finally, computerization made possible experiments that could generate data, test theories and produce economic models. Implementing auction schemes required new software and networked computers.

Personal computers and the internet (since 1981)

In 1981 IBM introduced the Personal Computer (PC), which supported a range of programming languages, though its capacity was initially limited by data storage being confined to 5¼ inch floppy diskettes. Larger scale applications had to await the fitting of 10MB hard drives in 1983. Mainframe computers, often with punched card input remained the staple of economic computing for much of the decade, for it was not till after 1985 that software written for mainframes gradually spread to PCs. New software developed to run under Microsoft's new operating system, MS DOS, in particular STATA, handled data management, graphical analysis, time series, cross section and panel econometrics. The software business expanded and diversified. Alongside the special purpose software economists understood were necessary for the spread of their techniques (PLATO and MUDA for experiments, AUTOBOX for time series, Winsolve for Real Business Cycle modeling, BACC for Bayesian analysis), general purpose software was widely used, as well

[7] For a history of simulation in economics, see Morgan (2012, ch.8)

as a new type of package based on high level programming and matrix language (Gauss, Matlab, R).

As the internet developed, the possibilities for new sources of data increased dramatically, especially when computerization of business created new sources of data. Computerization of financial markets in the mid-1980s made possible the use of high-frequency data, first in equity markets (in the 1980s) and then in foreign exchange markets (in the 1990s). Economists were quick to see the potential of minute-by-minute or transaction-by-transaction data for studying what has been termed the “microstructure” of markets, but this involved not just having computers sufficiently powerful to analyze large data sets but also getting access to the data.[8] Private suppliers of data were sometimes reluctant to make it available to academics. For example, Charles Goodhart, for an early study of foreign exchange markets, had to resort to filming the screen on which prices were being broadcast, using a video camera, and then replaying the tape to transcribe the numbers.[9]

Developments in hardware and software gave economists greater independence in their computer-based practices, which fostered two types of development. Computer-related practices were institutionalized through the establishment of journals, societies and institutes. The journal *Computer Science in Economics and Management*, was founded 1988. The Santa Fe Institute began operating in 1984, the Society for Computational Economics was founded in 1995, the Argonne/University of Chicago Institute on Computational Economics was

[8] There was also great interest in the theoretical analysis of the microstructure of financial markets at this time (e.g. Kyle 1985; Glosten and Milgrom 1985). The relationship between such theoretical work and empirical work needs further research.
[9] Our source is a conversation with Goodhart.

founded in 2007. This period saw the emergence of textbooks and manifestos for new ways of doing economics, from the first Santa Fe manifesto on “the economy as an evolving complex system” to the advocacy of agent-based modeling Doyne Farmer and Duncan Foley published in *Nature* in 2009.

The flourishing computer-based economic modeling strategies received very varied attention from the bulk of economists. Econometrics had become such a routine activity that with the exception of a few specialists in economic theory, most young economists engaged in some form of data analysis or other computer-based practices. Computer-assisted experiments had benefited from better infrastructure, as exemplified by Vernon Smith’s Arizona *Economic Science Lab* and Charles Plott’s Caltech *EPPS lab*, founded in 1985 and 1987 respectively. Computerization and the internet were also important through the development of large private markets such as Ebay and Amazon, creating a demand from business for expertise in areas such as mechanism design and experiments. IT giants such as Google and Microsoft invested heavily in economic expertise. Other approaches to economic modeling fostered by computerization include Santa Fe’s agent-based Modeling (Axtell and Epstein 1996), numerical methods (Judd 1998) and automated theorem proving (Kerber Rowat 2014).

3. What do computers do for economists?

The most obvious role for computers has been to **improve the speed and accuracy with which routine calculations are performed**. This is clearest in the earliest uses of computers to solve input-output models, to estimate regression coefficients and to simulate. In such cases, they were performing tasks that would otherwise be done "manually" using desk calculators. Such applications of computers need not involve any change in the way economists conceive their subject: they can simply work more efficiently. Some agent-based modeling also falls into this category. However, at some point the in increase computing power increases the complexity of the problems that can be solved to the extent that it becomes more appropriate to see computers as **enabling economists to solve new problems**. This happened very early. Orcutt's work on autocorrelation in the late 1940s involved a volume of calculations that would have taken so long to do manually that it amounts to a new way of analyzing data. Related to this is **enabling economists to develop or try out new techniques**. When the National Bureau of Economic Research (NBER) Computer Research Center for Economics and Management Science, extended TROLL after 1972, one of its aims was allowing the development of new techniques, partly through allowing users to combine a variety of methods. One of the techniques they developed was the Kalman Filter, and its extension the Hodrick-Prescott filter (see Boumans 2004, pp. 240-2). Likewise, resampling techniques such as bootstrapping or jackknifing had been theorized in the late 1940s, but, according to LSE statistician James Durbin, were not implemented for decades because "the computing problem was really rather severe" (Phillips 1988, 137).

Computers also **enabled economists to run simulations or experiments that generate new evidence.** Such work blurs the boundaries between theoretical and applied research. When Alvin Hansen and Paul Samuelson simulated the behavior of the multiplier-accelerator model in 1939 (calculations that were too simple to need computers, though the principle is the same) they were investigating the properties of a theoretical model, concerned with all possible parameter values. Had they gone on to compare the behavior of their system with data on economic activity, as Ragnar Frisch had done earlier in the 1930s, we might describe the same exercise as applied (it certainly would have been had they calibrated their coefficients in the light of what they found). From here, there is a continuum through guessed parameter values to parameter values that are derived from real-world data. In the early 1950s, when digital computing was still very rudimentary, analog computers were used extensively for simulation, not just of business cycles (e.g. Strotz et al 1953) but also market equilibrium (e.g. Enke 1951; Strotz et al 1951) and the behavior of inventories (e.g. Morehouse et al 1950).

Such work took off in the years around 1960, with the increased availability of digital computers (see Morgan 2004). Martin Shubik produced a bibliography on "Simulation, gaming, artificial intelligence and allied topics" (1960) that cited nine books, three bibliographies and 147 articles on simulation, with a further two books and 37 articles on "Monte Carlo". Given that the boundaries between categories were blurred, items in the "systems" and "gaming" categories might also have involved simulation. For example, the borderline between experiments (real decision makers in a simulated environment) and simulation (where the results are simulated) was far from clear cut (Morgan 2004, p. 355. A symposium on simulation in the *American Economic Review* the same year showed the breadth of work encompassed by simulation: business simulations, simulation of individuals and entire systems.

Computing also allowed the increased and more reliable **storage, retrieval and graphical exploration of bigger pre-existing data sets**. In his reminiscience, Durbin (in Phillips 1988, 139), for instance, shows acute awareness that statistical techniques have to be kept "simple, or applied workers don't use it." He recalled, "I thought the cumulative periodogram […] would provide applied workers in econometrics with a practical way of looking at the higher autocorrelation properties of a series […] I did meet a number of people who had got it programmed as part of regression packages, but they had not gotten the graphics in. They only had the result of the formal test […] So the outcome was a little disappointing in terms of practical take-up." By the late 1990s, software routinely allowed graphical display of results. This user-friendliness was, according to Holly Sutherland (1999), was the key to the influence that economic models – tax microsimulations, for instance – could have on applied research and policy design.[10]

Hardware and software improvements also enabled the **generation of new data** such as real-time data on individual transactions and behaviors were increasingly recorded in actual markets, but data were also generated via experimentation in economists' laboratories.[11] The ability to process very large data sets has been crucial to recent work in micro-econometrics. These developments came later for technological reasons. Dramatic increases in the speed of computation came about in stages, some very early, but developments in data storage and retrieval were greatly stimulated by the growth of networking and the internet in the late 1970s and 1980s. It was not until the 1970s that large data banks were developed for both academic and commercial use, and hence econometric software took time to reflect this. Subsequent watersheds occurred as various markets were computerized, enabling real-time data on behaviors and prices to be recorded: trading data in

[10] Verena Halsmayer (this volume) similarly explained that the visual display of simulations was central in convincing Norway policy-makers to use Leontief's multi-sector growth model for planning purpose.

the late 1980s, then government and private market data in the 2000s (Einav and Levin 2014). These "big data" sets are growing rapidly and cannot be studied by means of traditional techniques, which is in turn fostering the development of **new empirical techniques**, such as machine learning. For example Susan Athey, Guido Imbens and others have attempted to merge machine learning with causal inference techniques (Athey and Imbens 2015b).[12]

These developments have contributed to the realization of the hopes expressed by Tjalling Koopmans (1957) that existing models would prove to be the prototypes of more general and more realistic models through **relaxing the constraints on theoretical modeling**. This covers both the size of models and their complexity. Thus input-output models have been disaggregated and with the development of computable general equilibrium models, some of the restrictions imposed by linearity have been removed. Macro-econometric models increased enormously in size but reached their peak in the 1970s, when the largest models comprised thousands of equations, after which the constraint on their size ceased to be computing power but became the perceived theoretical incoherence of such large models. Some economists now hope that new techniques such as agent-based modeling will make it possible to remove clearly unrealistic assumptions such as that of the representative agent (Geanakoplos et al. 2012).

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[11] See Friedman 1989 for a detailed exposition of how computers changed the way data are collected, why they are collected, and what we want the data to tell us.

[12] On machine learning, see http://www.quora.com/How-will-machine-learning-impact-economics?redirected_qid=6706789. This is not to say that the development of more, better and more diverse data in economics has been driven solely by computerization. Authors have emphasized policy demands, the need to quantify the self, and many other factors. Nor is the problem of storing, retrieving and analyzing data specific to the post 1970 era (see for instance Lemov 2015).

At the beginning of the 1980s, a team at the Argonne National Laboratory, near Chicago, developed an Automated Reasoning Assistant (AURA; see Dick 2011). When used alongside inputs from human mathematicians, this work has challenged mathematicians' ideas about proofs. Such automated theorem proving has only recently been applied to economics but its proponents argue that it has the potential to transform economic theory. It can **prove known theorems** (e.g. Tang and Lin 2009, Kerber, Rowat and Windsteiger 2011) or **discover new theorems** (e.g. Tang and Lin 2011; Geist and Endriss 2011; see also Chatterjee and Sen 2014), for instance in game theory or social choice theory. Perhaps, more important than either of these is that, through providing new ways to approach theories, these methods **challenge traditional concepts of proof**. If "human thinking has been reconfigured through interactions with computing machinery" in mathematics, why might the same not happen in economics (Dick 2011: 494)? Kenneth Judd (1997), for instance, has relentlessly argued that computational methods could expand the role of economic theory, which need not be confined to proving theorems. Other fields such as computational social choice, have adopted computational methods of proof.[13]

Because of the involvement of economists in creating new markets, such as for permits to emit harmful gases or for the right to use parts of the radio spectrum for telecommunications, the emergence of **new markets requiring new modes of analysis** should not be seen as a factor external to economics. New online markets using sophisticated types of pricing, new types of auction, digital networks, and new types of economic transactions have induced computer scientists to draw on economists' expertise in

[13] This is probably tied to the fact that computer scientists, more than economists *per se*, have pursued the program outlined in Barthioldi, Tovey and Tricks 1989.

game theory and market analysis and economists have turned to computer scientists' algorithms and tools in order to analyze these markets. A recent introduction to the topic justifies the turn to computer science by arguing,

> Marshallian and Walrasian equilibrium analysis are not theories of how markets function. Their institution-free approach to predicting market outcomes precludes them from asking questions such as: When do market institutions fail? How do they behave when they fail? How should markets be designed to minimize failure, and what tradeoffs with market efficiency arise in do-ing so? Research in economics arising from general equilibrium and welfare economics has been concentrated on market imperfections. Computer scientists have paid relatively more attention to the nuts and bolts of market mechanisms and the robustness of market institutions. (Blume et al. 2015: 2)

The authors suggest that such methods have the potential to change the way markets are conceived, seeing work on mechanism design as re-opening issues debated in the 1930s in the socialist calculation debate. At a deeper level eventually, it would seem that it is not merely computing machines which are changing the face of economics, but the science behind the machine which is doing this. Economists have been prone to build economic mechanisms into machines (for instance Philips's MONIAC). They have therefore gradually resorted to computer science analogies to understand how economic agents think and how markets work. It has been argued that interest has shifted from human behavior to the behavior of markets and that algorithmic metaphors have been used to understand this (Mirowski 2007; c.f. Mirowski 2002).

4. Theory and application

How far did computers transform the relationship between theory and applied work?

This account of what improvements in computing have done for economists is sufficient to challenge the canonical view that developments in computing *inevitably* encouraged empirical work at the expense of theory. It shows that computerization stimulated new practices, from calibration to mechanism design and simulation, which changed the relationships between theory and applied work: they changed the way economists construct and use models.[14] According to many economists, it is such changes in modeling practices that have enabled some of the most important leaps in economics knowledge to take place. Deaton (2013) noted that what was holding consumer theory back in the 1950s was neither the dearth of data nor the lack of computational power: what was needed was new theory, framed using mathematical tools that would make it possible to implement the theory so as to make sense of seemingly contradictory empirical evidence. He therefore concluded that Gorman's duality theory was a prerequisite to the computerization of consumption models. Likewise, in the 1980s, solving the stochastic difference equations of the emerging Dynamic Stochastic General Equilibrium (DSGE) models appeared problematic. "Pencil and paper" solutions were not available (and are still generally not). There was, Fernandez-Villaverde (2010) argues, a need for new tools that made the estimation and evaluation of DSGE models feasible on desktop computers: this in turn required refinements in both estimation techniques, such as Bayesian analysis and Markov Chain Monte Carlo methods, and solution methods based on linearization and filtering.

According to Al Roth 2002, computerization profoundly changed in the way models were written down and what theory was expected to yield. He argues that the interbreeding of game theory, experimental and computational economics that gave birth to mechanism design pushed economists to conceive matching algorithms to redesign labor market for American doctors. They would explore the properties of such algorithms in various computational experiments, which in turn led to adjustment in the theoretical framework.[15] Some new methods further blurred the boundaries between theory and application. For example, agent-based modeling is a way of modeling that doesn't fit the theory/empirical divide, since models not conceived first, then encoded, but are directly conceived as computer programs (Gilbert 2008). Interestingly, the computerization of economics has been associated with (or has induced) a quest for new epistemological foundations. Simulation has been (re)conceived as a third way of doing science (Ostrom 1988). It has been argued that the knowledge economists generate is primarily case-based rather than rule-based, implying that reasoning is by analogy, irrespective of whether knowledge is based on theory, experiment or empirical work. This would place theory and applied work on an equal footing (Gilboa et al. 2014).

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[14] It is probably no coincidence that one of the few discussions of simulation, a computer-intensive activity, is found in a study of modeling (Morgan 2012, chapter 8).

[15] Roth (2002, 1363) explains that "the availability of computation meant that the design effort could proceed without waiting for theoretical resolution of outstanding problems Computation was used in several quite different ways in the course of the design and evaluation of the new medical labor market […] (1) Computational experiments were used in the algorithm design. (2) Computational explorations of the data from previous years were used to study the effect of different algorithms. (3) Theoretical computation, on simple

Yet, transformational as the spread of computers was for economists' practices, it seems that its promises of providing a new integration of theoretical and applied work remained largely unfulfilled. Most tools and approaches allowed by computerization, from automated theorem proving to computational social choice, from numerical approximation to agent-based modeling, have remained challenger methodologies, confined to specialized journals. Several explanations of economists' reluctance to embrace these approaches have been provided. Veluppilai (2011) singles out economists' commitment to an essentially Hilbertian paradigm (proofs *à la* Debreu), and argues that an algorithmic revolution is needed. Judd (1997) attributes the slow acceptance of computational methods to the reluctance of journal editors to accept such work because they don't constitute adequate proofs. Where automated reasoning does lead to a new proof, it is sometimes possible to find a traditional proof, and in such cases it is natural to use this rather than take the risk that an editor may not accept the computerized methods by which it was found.[16] It is only the use of Monte Carlo simulations, and some brands of simulation designed to explore or illustrate the behavior of mostly macro-economic models, that has spread widely. In other words, simulation is used only as a computational empirical device, or when analytical proofs are impossible. Lehtinen and Kuorikoski (2008) argue that economists' reluctance to use simulation as a theoretical tool is grounded in their conception of understanding, which requires that an analytical derivation from a set of fundamental axioms is established. To put this crudely, for some economists, explaining a phenomenon means deriving it from the

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markets to which existing theoretical results apply, was used to understand the effect of market size."

[16] For example, Kerber and Rowat (2014) found a proof using automated reasoning but once found, they chose to present a traditional proof.

assumption of rational choice.[17] Additionally, economists may be more interested in how a process unfolds rather than either whether causality can be proven or having precise numbers; they have often faulted computer simulation for being a "black box."

That computerization has failed to transform theorizing and the relationship of theory to applied work stands in contrast to what happened in other sciences. In biology, based on analogical reasoning, computerization enabled the expansion of computational biology. In physics, simulation was understood sometimes as a sampling technique, a tool for the solution of integro-differential equations, and as a modeling technique for complex physical processes. This variety of approaches, as well as the variety of application to nuclear fission, meteorology, chemistry or fluid physics helped creating a subculture and language within the discipline, a "trading zone" in the words of Peter Galison 1997, in which simulation was made an acceptable method of inquiry for physicists. In postwar linguistics, computers were used both to formalize linguistic theories, that is, to implement mathematized syntax and manipulate natural language structures, and as an hypothesis-testing tool (Martin-Nielsen 2012).

Economists' selective appropriation of empirical techniques fostered by computation

The role computerization played in economics is thus paradoxical. True, it allowed faster computation, and enabled the development of a whole array of new empirical techniques and approaches. Yet, it largely failed to transform economists' ideas about economic knowledge and how to generate it. On a closer look, furthermore, the rise of applied economics that

[17] Not all economists accept either an axiomatic approach or reduction to rational choice as the hallmark of explanation. For example Solow (1997) draws a sharp distinction between an

computerization has purportedly fueled was highly selective. In particular, some of the most computationally-intensive approaches were marginalized at the turn of the 1980s, despite getting the computational power they were longing for. Large-scale macroeconometric models, for instance, were difficult to build in the 1960s and 1970s because of physical constraints. Hundreds of (physical) pages of Fortran code had to be written and debugged; data often had to be punched into cards for storage and input, each card possibly holding less than a dozen numbers, (and it was easy to drop a stack of cards on the floor) and when the output came it would be spread across many metres of fanfold paper. Much still had to be done with pencil and paper, including the plotting of graphs.[18] For example, when a macroeconometric model was being constructed by economists from MIT, the Federal Reserve Board and the University of Pennsylvania between 1965 and 1972, doing the first simulation took several months. Modern GUI-based software removed many of these difficulties, keeping track of everything, meaning that the econometrician's desktop came to look very different. Yet, as computers grew faster and software integrating a wider range of techniques, procedures to easily store and retrieve data and plot results (Renfro 2007), the empirical results and theoretical and methodological foundations of these models were increasingly challenged. These models, the largest of which had around two thousand equations, produced by large teams of researchers failed to predict better than simpler models (Fromm and Klein (1976)) and their theoretical foundations were challenged. As a result, even though it was now much easier to construct and run the models, academic economists lost interest in them. However, this did not mean they were abandoned: instead, during the

axiomatic approach and model-building.

[18] The graphs output by early econometric software involved printing ASCII characters in suitable places on a large sheet of paper. Instead of a line, a variable would be indicated by a

1980s, they were pushed out of academia into private forecasting firms, such as Data Resources Incorporated, Wharton and Chase Econometrics, often established by the models' creators.

Macroeconomists did take up computers but their use in DSGE modeling and macro-econometric time-series analysis was very different from the use that the builders of increasingly complex large-scale forecasting models would have anticipated. We are thus uncertain about how computers play out in the adoption of new models and empirical techniques in macroeconomics. The rise of calibrated business-cycle models, then calibrated and estimated DSGE, seems to be predicated on controversies over theoretical insights and perceived biases in econometric techniques rather than a response to computer power shortage or advances. Yet, the success of DSGE modeling may have been predicated, in part, on the ability of its proponents to yoke to the improvement of hardware and computer languages, by shaping mediating tools. "No matter how sound were the DSGE models presented by the literature or how compelling the arguments for Bayesian inference," Fernandez-Villaverde 2010 writes, "the whole research program would not have taken off without the appearance of the right set of tools that made the practical implementation of the estimation of DSGE models feasible in a standard desktop computer. Otherwise, we would probably still be calibrating our models." Crucial to the development of the DSGE approach was not only Bayesian estimation and Markov Chain Monte Carlo methods, but also their translation into software such as BRAP and DYNARE. The development of software has been central to computerization of the discipline (Renfro 2007). Time series has a variety of

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series of asterisks, the degree of precision limited by line spacing and character widths of the font.

user-friendly packages, experimentalists developed MUDA, and some agent-based proponents believe their approach would be more widely accepted if they developed software that is easy to use.

That experimental economists in the 1970s and 1980s immediately understood that the development of their own software was key to development of newly established computerized experimental laboratories played a role in the "experimental turn": Stephen Rassenti's constant updating of PLATO at Vernon Smith's Economic Science Laboratory gave them a head start, while MUDA, developed at Charles Plott's Caltech EEPS, was distributed to over ninety universities in the next years, thereby contributing to "the lowering of costs of entry to experimental economics" (Svorencik 2015, 99). Yet, what the case of experimental economics shows is that computerization, although a condition for the development of experiment and use by mechanism designers, for instance, was far from sufficient to ensure the success of the new approach. For instance, Svorencik 2015 argues that a lavishly funded computer laboratory set up at Berkeley in 1960 failed not because computing was inadequate but because its creator focused too much on building infrastructure and not enough on building a community: the recent take-off in experimental economics was required much more than the acquisition of suitable hardware. In the same vein, the success of the blend of game theory, experiments and computational science which came to be known as mechanism design required constant advocacy toward funders, public agencies, policy makers and business (Lee 2016).

The situation is even more complicated in microeconomics. A promising approach in the 1970s seemed to be Computable General Equilibrium, one that heavily relied on up-todate computational power to calibrate its models. These were so complex that in the last years of the 1970s, researchers had to shrink the number of variables and even when they had done this, a simulation could still take six hours. By 1981, the first desktop computers had been adopted, it was no longer necessary to shrink the number of variables and computation time was a matter of minutes. Yet, the computable general equilibrium community was divided on whether to use calibration and estimation, and their models were generally considered "black-boxes," some "a bit dubious, [..] produc[ing] results that cannot be traced to an accessibly small set of simple assumptions (Rauscher 1999, quoted in Ballard and Johnson 2016). Better hardware did nothing to curb the decline in computable general equilibrium modeling. And the empirical methods which would emerge triumphant from the 1980s crisis in econometrics, quasi-experimental techniques, appear much less computationally-intensive than the structural econometrics they were intended to supersede.[19] The bibliometric evidence provided by Biddle and Hamermesh (this volume) suggests that these new empirical techniques have been successful not through the redefinition of links between theory and applied work afforded by computerization, but through enabling empirical work to be undertaken without being tied to theory.

5. Concluding remarks

We do not wish to challenge the claim that the growth of computers was central to the transformation of economics in the past thirty to forty years. It clearly was. Economists have

[19] The development of new databases, as well as emulation with medical science, is central to the story told by David Card and Alan Krueger in a recent interview, but computers do not even appear once (see http://davidcard.berkeley.edu/interviews/interview%20with%20Card%20and%20Krueger.pdf 658867308). For a history of the "credibility revolution," see Panhans and Singleton 2016.

used computers to do many things that they could never have done without them and some of these practices have become central to the field. Rather, our claim is that the growth of computers is not sufficient to explain the turn towards applied economics that is documented in this volume. Beginning in the 1980s, some computationally very intensive techniques were marginalized, and computationally less demanding approaches based on quasi-experiments became widely used in microeconomics. Of course, most of these modeling strategies require a minimum hardware and software equipment beyond anything that was available a few decades ago, but beyond this basic level, we suggest that computerization is neither sufficient nor sometimes even necessary to explain the success of the those empirical approaches that have been widely adopted

The story of the transformation of applied economics therefore needs to be related not just to the rise of computing but to other dimensions of the context in which economists were working: to policy challenges, such as the creation of new types of market (McMillan 2003), to changes in the issues that concerned economists, to social changes such as the acceptability of making proprietary data available to researchers (Taylor et al. 2014), and to new demands from business.[20] The impact of computerization was itself conditional upon the development and implementation of strategies for bringing models to the machine, such as the development of coding skills, software, laboratories, training programs, and interdisciplinary communities. Finally, in order to understand how economics was transformed, and the turn to applied economics, account needs to be taken not only of the rise of computing but of how economists conceived economic theory and its relationship to empirical work. Though the rise of computers could be studied in relation to either theory (very limited impact) or

[20] https://www.quora.com/Why-do-technology-companies-hire-economists-and-what-is-their-contribution?redirected_qid=6705502

application (substantial impact) in isolation, it is more useful to take a broader view. It is possible that the eventual effect of computerization will be to challenge accepted notions of theoretical and applied work.

Bibliography

Adelman, I. (undated) The research for the paper on the dynamics of the Klein-Goldberger model, Retrieved March 1, 2016, from http://web.stanford.edu/~clint/tmp/milestones.pdf

Adelman, I. & Adelman, F.L., 1959, The dynamic properties of the Klein-Goldberger model, *Econometrica*, pp. 596-625.

Alker, H.R., 1974, Computer simulations: inelegant mathematics and worse social science, *International Journal of Mathematical Education in Science and Technology* 5, pp. 139-55.

Athey, S. & Imbens, G., 2015a, *Recursive Partitioning for Heterogeneous Causal Effects,* working paper.

Athey, S. & Imbens, G., 2015b, Machine learning methods for estimating heterogeneous causal effects, https://faculty-gsb.stanford.edu/athey/documents/HeterogeneousEffects.pdf.

Axtell, R.L. and Epstein, J.M., 1996, *Growing Artificial Societies: Social Science from the Bottom Up.* Cambridge, MA: MIT Press.

Augier, M. & Feigenbaum, E., 2003, Herbert A Simon, *Proceedings of the American*

Philosophical Society, 147(2).

Bartholdi, J., Tovey, C.A., and Trick M.A. 1989. "Voting schemes for which it can be difficult to tell who won the election" *Social Choice and Welfare*

Beneke, R., 1994, On becoming distinguished, in J. Langley, G. Vocke and L. Whiting (eds) *Earl O. Heady: His Impact on Agricultural Economics*, Ames, IA: Iowa State University Press.

Blume, L., Easley, D., Kleinberg, J., Kleinberg, R. & Tardos, 2015, Introduction to computer science and economic theory, *Journal of Economic Theory*, 156, pp. 1-13.

Boumans, M. J., 2004, The reliability of an instrument. *Social Epistemology*, **18**, 215-246.

Brown, J.A.C., Houthakker, H.S. & Prais, S.J., 1953, Electronic computation in economic statistics, *Journal of the American Statistical Association*, 48(263), pp. 414-28.

Chatterjee, S., and Sen, A., 2014, Automated Reasoning in Social Choice Theory: Some Remarks, *Mathematics in Computer Science* 8, pp. 5-10.

Dantzig, G.B., 1990, The diet problem, *Interfaces*, 20(4), pp. 43-7.

Dawkins, R. 1996. *Climbing Mount Improbable*. London: Viking.

Deaton, A. 2013, Puzzles and paradoxes: a life in applied economics, in M Szenberg & L Ramrattan (eds), *Eminent Economists II: Their Life and Work Philosophies,* Cambridge University Press, Cambridge, also at https://www.princeton.edu/~deaton/downloads/deaton_puzzles_and_paradoxes_v1_5_11_17_11.pdf.

Dick, S., 2011, AfterMath: The work of proof in the age of human--machine collaboration, *Isis*, 102(3), pp. 494-505.

Dick, S., 2015, Of Models and Machines: Implementing Bounded Rationality, *Isis*, 106(3), pp. 623-634.

Einav, L. & Levin, J.D., 2014. "The data revolution and economic analysis," in Lerner J., Stern S. (eds). *Innovation Policy and the Economy*. Chicago: University of Chicago Press.

Enke, S., 1951, Equilibrium among Spatially Separated Markets: Solution by Electric Analogue, *Econometrica* 19(1), pp. 40-7.

Enns, J. Wolf, C. 1971. "Computers and Economics: Progress, Problems and Prospects." RAND memorandum, retrieved October 2016 https://www.rand.org/content/dam/rand/pubs/papers/2006/P4724.pdf.

Farmer, J. D., and Foley, D., 2009, The economy needs agent-based modelling, *Nature* 460 (August 6), 685-6.

Forrester, J.W., 1958, Industrial dynamics: a major breakthrough for decision makers, *Harvard business review*, 36(4), pp. 37-66.

Friedman, H. 1989. "Modern Statistics and the Computer Revolution," retrieved May 2016, http://www.ssc.upenn.edu/~fdiebold/NoHesitations/Friedman.pdf

Fromm, G. Klein, L. "The NBER/NSF Model Comparison Seminar: An Analysis of Results." In Berg, S.V. (ed) *Annals of Economic and Social Measurement 5(1)*. NBER publishing.

Geanakoplos, J., Axtell, R., Farmer, D.J., Howitt, P., Conlee, B., Goldstein, J., Hendrey, M., Palmer, N.M. & Yang, C.-Y., 2012, Getting at systemic risk via an agent-based model of the housing market, *The American Economic Review*, 102(3), pp. 53-8.

Geist, C., and Endriss, U., 2011, Automated Search for Impossibility Theorems in Social Choice Theory: Ranking Sets of Objects, *Journal of Artificial Intelligence Research* 40, pp. 143-174.

Gilbert, N., 2008, *Agent Based Models,* Sage, Los Angeles and London.

Gilboa, I., Postlewaite, A., Samuelson, L. & Schmeidler, D., 2014, Economic Models as Analogies, *Econ J*, 124(578), pp. F513-33.

Glosten, L.R., and Milgrom, P.R., 1985, Bid, ask and transaction prices in a specialist market with heterogeneously informed traders, *Journal of Financial Economics* 14, pp. 71-100.

Goldberger, A.S., 2004, Econometric computing by hand, *Journal of Economic and Social Measurement*, 29(1-3), pp. 115-7.

Gruenberger, F.J., 1968, *The History of the Johniac, RAND Memorandum RM-5654-PR,* RAND Corporation, Santa Monica.

Halsmayer, Verena. 2016. *Modeling, measuring, and designing economic growth. The neoclassical growth model as a historical artifact.* Unpublished PhD thesis, Universität Wien.

Hamermesh, D.S., 2013, Six Decades of Top Economics Publishing: Who and How? *Journal of Economic Literature*, 51(1), pp. 162-72.

Judd, K.L., 1997, Computational economics and economic theory: Substitutes or complements? *Journal of Economic Dynamics and Control*, 21(6), pp. 907-42.

Judd, K. L., 1998, *Numerical Methods in Economics*, Cambridge, MA: MIT Press.

Kerber, M., Rowat, C., & Windsteiger, W., 2011. Using Theorema in the Formalization of Theoretical Economics, *Lecture Notes in Computer Science*, vol 6824, pp. 58 - 73.

Kerber, M. and C. Rowat, 2014, Sufficient conditions for unique stable sets in three agent pillage games, *Mathematical Social Sciences*, 69, pp. 69-80.

Koopmans, T.C., 1957, *Three Essays on the State of Economic Science,* McGraw Hill, New York.

Kyle, A.S., 1985, Continuous auctions and insider trading, *Econometrica* 53(6), pp. 1315-1336.

Lee, K.S. 2016. "Mechanism Designers in Alliance: A Portrayal of a Scholarly Network in Support of Experimental Economics," *History of Political Economy* 48 (2), 191-223.

Lehtinen, A. and Kuorikoski, J. 2008. "Computing the Perfect Model: Why Do Economists Shun Simulation?" *Philosophy of Science* 74, 304-329.

Lemov, R., 2015. *Database of Dreams: the Lost Quest to Catalog Humanity*. Yale: Yale University Press.

Martin-Nielsen, J. 2012. "'It was All Connected': Computers and Linguistics in Cold War American" in Solovey, M. Cravens, H. (eds). *Cold War Social Science: Knowledge Production, Liberal Democracy, and Human Nature*. New York: Palgrave MacMillan.

McMillan, J., 2003, *Reinventing the Bazaar: A Natural History of Markets,* Princeton University Press, Princeton, NJ.

Mirowski, P., 2002, *Machine dreams : economics becomes a cyborg science,* Cambridge University Press, Cambridge; New York.

Mirowski, P., 2007, Markets come to bits: Evolution, computation and markomata in economic science, *Journal of Economic Behavior & Organization*, 63(2), pp. 209-42.

Morehouse, N. F., R. H. Strotz and S. J. Horwitz, 1950, An Electro-Analog Method for Investigating Problems in Economic Dynamics: Inventory Oscillations, *Econometrica* 18(4), pp. 313-28.

Morgan, M., 2004, The birth of a technology to create 'evidence" in economics. *Revue* *d'histoire des sciences*, **57**, 339-375.

National Science Foundation/National Bureau of Economic Research, 1976. [To be supplied]

Newlyn, W., 2000 The origins of the machine in a personal context. In R. Leeson (ed.) *A. W. H. Phillips: Collected Works in Contemporary Perspective*. Cambridge: Cambridge University Press.

Orcutt, G.H., 1948, A new regression analyser, *Journal of the Royal Statistical Society. Series A (General)*, 111(1), pp. 54-70.

Orcutt, G.H. & Cochrane, D., 1949, A Sampling Study of the Merits of Auto-regressive and Reduced Form Transformations in Regression Analysis, *Journal of the American Statistical Association*, 44(247), pp. 356-72.

Orcutt, G.H. & James, S.F., 1948, Testing the significance of correlation between time series, *Biometrika*, 35(3/4), pp. 397-413.

Phillips, P. 1988. "The ET interview: James Durbin" *Econometric Theory* 4: 125-57

Renfro, C.G., 2004, Econometric software: The first fifty years in perspective, *Journal of Economic and Social Measurement*, 29(1-3), pp. 9-107.

Renfro, C. G., 2011, Econometrics and the Computer: Love or a Marriage of Convenience? *History of Political Economy*, 43(Supplement 1), pp. 86-105.

Roth, A.E., 2002, The economist as engineer: Game theory, experimentation, and computation as tools for design economics, *Econometrica*, 70(4), pp. 1341-78.

Ruggles, N., 1970, *Economics*, Englewood Cliffs, NJ: Prentice Hall.

Samuelson, P.A. 1966, Market mechanisms and maximization, in JE Stiglitz (ed), *The Collected Scientific Papers of Paul A. Samuelson,* MIT Press, Cambridge, MA, pp. 425-92.

Shubik, M., 1960, Bibliography on simulation, gaming, artificial intelligence and allied topics, *Journal of the American Statistical Association,* 55, pp. 736-51.

Slater, L.J., 2004, EDSAC: Recollections on early days in the Cambridge Computing Laboratory, *Journal of Economic and Social Measurement*, 29(1-3), pp. 119-22.

Solow, R. M., 1997, How Did Economics Get That Way and What Way Did It Get? *Daedalus* 126(1):39-58.

Stevenson and Wolfers, 2012. "Business is Booming in Empirical Economics." *Bloomberg View http://www.bloomberg.com/view/articles/2012-08-06/business-is-booming-in-empirical-economics.*

Strotz, R. H., J. F. Calvert and N. F. Morehouse, 1951, Analogue computing techniques applied to economics, *AIEE Transactions* 70, pp. 557-63.

Strotz, R. H., J. C. McAnulty, and J. B. Naines, 1953, Goodwin's Nonlinear Theory of the Business Cycle: An Electro-Analog Solution, *Econometrica* 21(3), pp. 390-411.

Sutherland H., 1999, "Information technology and the development of economic policy: the use of microdata and microsimulation models", in Coppock T. (ed*.), Information Technology*

and Scholarship: applications in the humanities and social sciences. Oxford: Oxford University Press

Svorenčík, A., 2015, The Experimental Turn in Economics: A History of Experimental Economics, *University of Utrecht: Utrecht School of Economics Dissertation Series*, 29.

Tang, P. & Lin, F., 2009, Computer-aided proofs of Arrow's and other impossibility theorems, *Artificial Intelligence*, 173(11), pp. 1041-53.

Tang, P. & Lin, F., 2011, Discovering theorems in game theory: two-person games with unique pure Nash equilibrium payoffs, *Artificial Intelligence*, 175(14), pp. 2010-20.

Taylor, L., Schroeder, R. & Meyer, E., 2014, Emerging practices and perspectives on Big Data analysis in economics: Bigger and better or more of the same? *Big Data & Society*, 1(2).

Vellupillai (2011). Toward an Algorithmic Revolution, *Journal of Economic Surveys,* 25(3), 401-430.

Vines, D., 2000, The Phillips machine as a "progressive" model. In R. Leeson (ed.) *A. W. H. Phillips: Collected Works in Contemporary Perspective*. Cambridge: Cambridge University Press.

Watts, H.W., 1991, Distinguished fellow: an appreciation of Guy Orcutt, *The Journal of Economic Perspectives*, 5(1), pp. 171-9.