CITR
Center for Innovation and Technology Research

CITR Electronic Working Paper Series

Paper No. 2014/7

Atanasoff's invention input and early computing state of knowledge

Philippe Rouchy

Department of Industrial Economics and Management, Blekinge Institute of Technology, SE-371 79 Karlskrona, Sweden
E-mail: philippe.rouchy@bth.se

June 2014

Abstract

This article investigates the dynamic relationship between a single pursue of an invention and the general US supply of similar activities in early computing during the 1930-1946 period. The objective is to illustrate how an early scientific state of knowledge affects the efficiency with which an theoretical effort is transformed into an invention. In computing, a main challenge in the pre-industrial phase of invention concerns the lack of or scattered demand for such ground-breaking inventions. I present historiographical evidences of the early stage of US computing providing an improved understanding of the dynamics of the supply of invention. It involves solving the alignment between a single inventor's incentives to research with the suppliers of technology. This step conditions the constitution of a stock of technical knowledge, and its serendipitous but purposeful organisation.

1. Introduction

This article makes a contribution to the literature on technical change (Nelson, 1959; 1962; 2007: 33-4) by clarifying a poorly understood chain of event starting from an inventor's incentive to solve a problem to the established state of knowledge in computing. To this end, the paper focuses on the early stage of US computing covering a period of 15 years, from roughly 1930 to 1946 where three means of calculation (electromechanical, relay and vacuum tubes) culminated toward electronics systems starting the new technological regime of computing (see Nordhaus' graph (2007: 144) and period selection below) with the ENIAC[1].

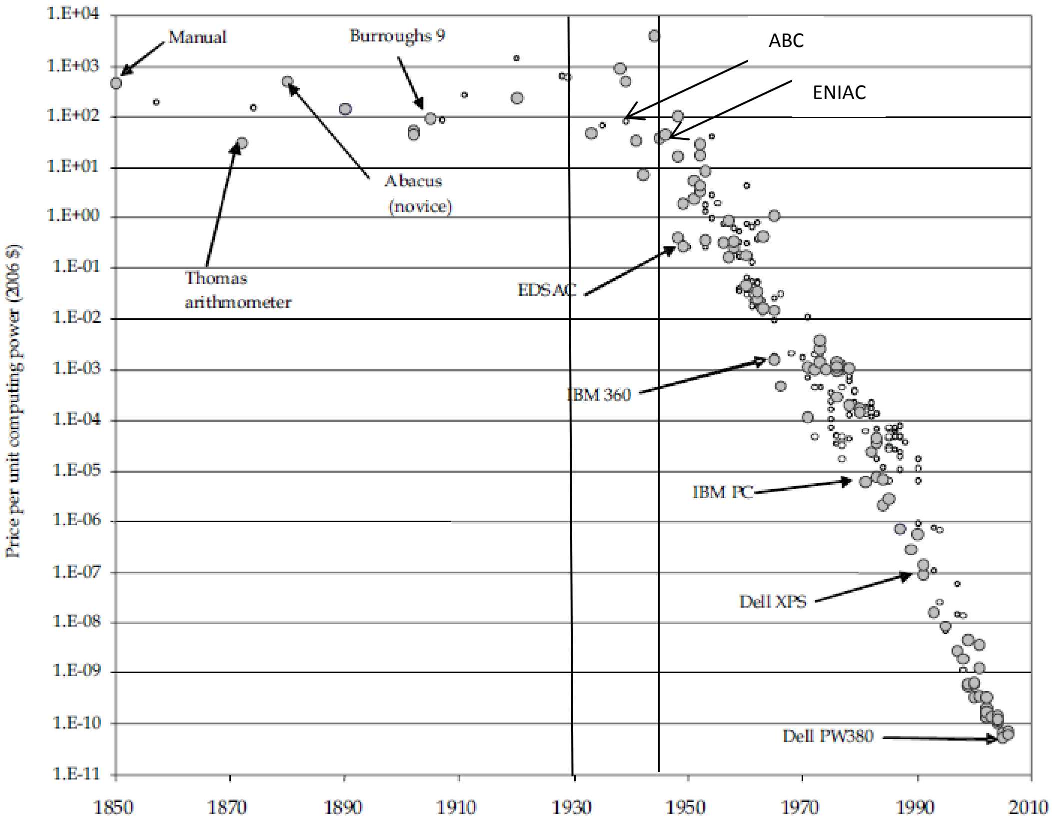

Fig. 1: Progress of computing measured in cost per computation per second deflated by the price index for GDP in 2006 prices. The period this paper covers is between the two vertical lines. Source: Nordhaus (2007).

The timeline of the investigation covers the period where scattered R&D done by dedicated individuals leads to invention. For that matter, I proceed to a historiographical (Ceruzzi, 1983, 1988; Cortada, 1993; David, 2001; Kuhn, 1977; Mahoney, 1988; Mokyr, 1990; Rosenberg, 1982: 3-33) reconstitution of John Atanasoff's endeavour to complete a computer prototype in 1942.

The paper maintains that the early development of US computing brings further evidences of the evolutionary model of technological change (Dosi & Nelson, 1994) regarding the state of technological knowledge. This model identifies linkages between stages of knowledge by articulating a given state of knowledge (1930's technological paradigm), the number of skilled people in the art (the start of a technological trajectory) and the state of the industry (a technological regime) implying market's offer and demand. It is evolutionary since it explains the movement of inventive activities over time, recalling why invention happen the way it did through overlaps. It is dynamic since the supply and demand of inventive activity provides a useful measure of its success or failure.

In view of this conceptual model, the paper specifies and interprets the dynamics of the evolution of computing invention thanks to three stages: (1) in the early stage of the creation of a new field, the condition of equilibrium between the supply of continuous invention and its demand do not exist. I show how Atanasoff's work following a logic of invention was nevertheless side-tracked from subsequent development trajectory of US computing. (2) The individual supply of scientific knowledge is an essential but not sufficient condition for reaching a homogeneous state of knowledge. For that matter, I compare Atanasoff's trajectory as an individual researcher to the state of knowledge in computing at the time of his creation. It is essential that many individual scientists identify a problem to solve. (3) Because technology is complex, i.e. made of composite sciences, the stage of useful invention is reached when a critical mass of individual scientists are working on solving similar issues. Between 1930-1946, the demand for computing does not yet exist rendering the cost of development extremely high (see fig.1, the position of Atanasoff's computer in Nordhaus's graph). Early stage and full scale experimentations can only be designed by firms and other institutions but rarely individuals. The special circumstances of the WWII will provide the incentive to subsidies large research facilities around unique computing projects (Goldstine & Goldstine, [1946] 1982; Stern, 1981). The main contribution of the paper is its employment of basic evolutionary thinking to illustrate how invention in early computing is an upward curve of supply of inventive activities whereby ordinary demand is temporarily replaced by subsidies from both private and public organisations (Mazzucato, 2014). The early stage of computing invention resembles schematically the technology push model in so far as the dynamic of invention is captured by agreements or frictions between technologist's incentive to participate and the enabling institutional framework making computing a large scale technology. The paper re-specifies existing model mix (Van Den Ende & Dolfsma, 2005) by unfolding (a) Schmookler's model of invention starting with (b) Atanasoff's logic of invention, its relation with (c) the supply and demand of existing inventions and finally (d) the significance of change brought by computing and its predictable control through research agencies.

2. The Schmookler's model of invention and the nascent computer industry

There is little research done on computing starting with the role individual inventors played in the early development of the industry. In computer historiography, John

Atanasoff emerged somewhat as a controversial figure. Here I focuses on John Atanasoff's skills and motivation to build a computer prototype. Scrutinizing Atanasoff's invention seeks to clarify the link between individual's endeavour involving tinkering, pride of authorship and instinct of contrivance (Kuznets, 1962: 23; Machlup, 1962: 144; Veblen, 1898; Taussig, 1925: 17) and further practical usefulness entering economic production. As Kuznets' shows, the usefulness of solving a practical problem distinguishes the technical invention from discovery and mere technological improvement. Discovery is abstracted and operated within the paradigm of a science without necessary application (cf. Kuhn's scientific paradigm shift, 1962) whereas technological improvement exists within a productive process requiring less effort and capacity than discovery or invention. With technical invention, it could be expected that it is more likely to participate in larger efficiency in production cost reduction or the creation of a new and cheaper technological goods. Classic economics assumes an effect of technical invention on the growth of economic production. Evolutionary economics has already pointed out the role of "tacit knowledge" and "endogenous learning activities" that deform evolution continually (Dosi & Winter, 2010: 86-8).

I suggests along with Hayek ([1936] 1948: 51) that in order to arrive to the stage where the technical invention corresponds to the stage of knowledge where the effect on economic production can be observed, we need to be more specific about the sort of knowledge that makes this connection possible. In economics[2], those events, or stages leading to an actual equilibrium between the cost and the price of an invention are generally treated as "frictions", "errors", "bad luck", "marginal" or "accidental" phenomena (Dosi & Nelson, 1994: 157). To understand the dynamics of the supply of invention, I specify "marginal" phenomena into Schmookler's determinants of industrial inventions (Schmookler, 1962: 196; Dosi & Nelson, 1994: 161). His model helps identifying three basic stages (1) the state of knowledge leading to an invention (technological paradigm); (2) the number of skilled people in the art incorporating the cost/profit in carrying out an invention (technological trajectory) and (3) the state of an industry, including gross/net profit in bringing out an innovation (technological regime). In this paper, the two first steps in the Schmookler's model helps us to characterise early electronic computer exemplified by Atanasoff's logic of problem solving and the general supply of inventions in computer related issues. The third step in Schmookler's model shows gaps in the market demand which precisely characterise the early stage of computing. Between 1930-1946, electronic computer technology does not reach market maturity. Important research institution will intervene at the junction between a non-existing demand function (not as a substitute) and an acceleration of a standardisation (supporting a discipline) brought by the circumstances of WWII.

3. Within Atanasoff's research agenda

John Atanasoff's research on computing started from a situation of workmanship one would naturally find during the development of research in theoretical and applied physics. To visualise Atanasoff's process of invention, I use Schmookler's diagram (Schmookler, 1962) focusing on the schematic steps involved in the creation of an invention (indicated in dark):

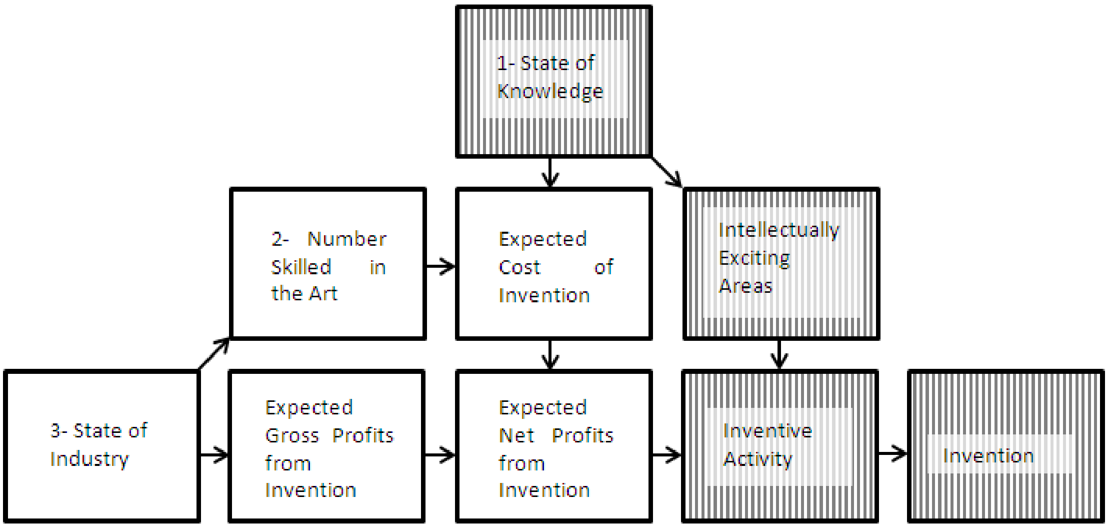

Figure 2: Schmookler's determinant of industrial invention (1962). The darker area represents the single inventor path taken by Atanasoff. The arrows signify "determines".

Machlup (1962: 158-9) description of the process of inventing is useful to approach Atanasoff's research agenda:

> First, the inventor is confronted with a problem, that is, with dissatisfaction about the ways certain things are done coupled with a feeling that there are better ways of doing them. Second, he tried to think of similar problems that have been solved before, which either are familiar to him or which he proceeds to study. This usually gives him clues for possible plans to be followed in the solution of his problem. Third, he carries out these plans, several of which may not work but may suggest other clues. Finally he finds a solution.

Here there are room for interpretation about the "inventive activity" coming from the drive of an individual to solve scientific puzzle and the state of technological knowledge at a given time[3]. Atanasoff came to the development of a computer prototype through the developments of his own scientific maturity through issues encountered during his studies and his Phd work on the polarizability of Helium (Smithsonian oral archives, 1969: 2). His thesis in quantum particle physics completed in 1930, entitled 'the dielectric constant of helium,' is a study of the relative permittivity of the polar molecules of helium. The object of the study consists in finding a reliable atomic characterisation of those molecules which are electrically dispersed due to their random orientation. Scientists use spectrometers to characterise the electric poles of molecules and proceed by extrapolation with various kind of mathematical functions to quantify, e.g. the chemical bounds of gas. Scientific work on molecular spectra requires calculating a large amount of data[4]. And in a letter to R. E. Buchanan at the committee on Patents (21 nov. 1940) Atanasoff wrote:

> This way the solution of large systems of linear algebraic equations constitutes an important part of mathematical applications…. The solution of general systems of linear equations with a number of unknowns greater than ten is not often attempted. But this is precisely what is needed to make approximate methods more effective in the solution of practical problems.

Ritz combination, Laplace equations, Fourier series or Hylleraas' wave function are different methods of calculation physicists can use to solve issues of frequencies of atomic spectral lines. They allow the researcher to know the spectral origins of atoms. Atanasoff had a number of PhD students who were working on such applied issues. For example, his student Charles Wells investigated the possibility of getting a reasonable mathematical approximation to the ground state of the lithium atom. The issue of calculation becomes difficult because the lithium atoms have three external electrons whose actual delineation is rendered difficult with the wave function method.

Successive students' works brought the issue of solving partial differential equations to Atanasoff's attention (Clarance Larson collection, 1985). The large linear differential equation provides more calculation power which modern physics can simply not do without. Solving large linear differential equation becomes a necessity: (1) when the problem becomes more complex and demands a larger system of linear equations and (2) when the problem incorporate multiple independent variables, it demands larger calculation capability (Atanasoff, [1940], 1973). Atanasoff, as a physician of his time, was looking for instruments of calculation to help him solve issues of mathematical extrapolation. The idea of building a computer did not come suddenly. He proceeded with a series of experiment including building electronic circuitry.

Beside his work in quantum physics, there are a number of contingencies that made Atanasoff choose to work in a mathematics and physics department rather than pure mathematics. He developed a steady interest in electronics. From 1930 to 1933, he came across a series of works such as handbooks on radio outfits, the vacuum tube theory by Van der Bijl, R. Willson's thesis on electronics applied to the dynamics of quartz. Some of his works in electronics is done partly in the context of his graduate experimental work and some by playing around with radio frequencies and vacuum tubes. By 1933, he graduated in electronic engineering. In the subsequent years of his PhD, Atanasoff was on his way to combine his various sources of information to envisage solving linear equations.

Atanasoff reviewed both analogue and digital computers available in his immediate environment. He had the opportunity to work with some of them. Atanasoff reviewed analogue[5] computing devices such as a slide rule, the Vannevar Bush's differential analyser (DA), an antiaircraft fire director, a Fourier analysis machine used by the Coast and Geodetic Survey, and created a tool, the two dimensional Laplaciometer. He also reviewed digital computers such as key driven machines (comptometer), Burroughs' book keeping machines, Monroe or Marchant's movable-carriage machines, IBM, Remington Rand tabulators. Those reviews and both his work and the practical issues of his students made him realise soon enough that solving the frequencies spectrum issue demanded to investigate a machine specifically design to calculate a system of linear algebraic equations.

In 1935, he got interested in mechanizing digital calculating machines. He investigated the only IBM tabulator that was available at his university used by A. E. Brandt at the statistics department. This episode with A. E. Brandt gives an indication of how Atanasoff investigates resources of his available professional environment to envisage possible solutions[6]. Calculation became a means to investigate the differences between analogue and digital machines and to find clues and methods to solve frequencies' problems of quantum physics (Smithsonian oral archives, 1969: 15). He wrote a paper with Brandt (1936) which allowed him to investigate the use of IBM punch cards having in mind the improvement of tabulator equipment to analyse complex spectra[7]. Atanasoff's means of inquiry reaches quickly its limits since he was not allowed to modify any characteristics of the IBM machine under the firm's restrictive technical support contract and did not belong to his department. He carried on his research by exploring further possibilities offered by the cheapest method available, i.e. the thought experiment. The thought experiment consisted in finding out how the analysis of complex spectra could function on the set-up of the IBM tabulator. Atanasoff started to consider systematically what should be modified on the existing IBM machine to run *his problem*. Atanasoff (Smithsonian oral archives, 1969: 10-1) recalls:

> (...) IBM, they had disciplined their repairmen and their repairmen were generally agreeable, but they wouldn't discuss the internal technical aspects of the equipment very much; either because they didn't know it or because they were told not to discuss it. So I was determined to do something with IBM equipment and, it says here in '34 and '35 that Brandt and I worked on the use of IBM punch card equipment to analyze complex spectra. I have a -- we have a publication on this. What I did was to guess how I would -- I had to get inside the computing machine and I wasn't allowed to change circuits, you see. So I had to guess how I would have built it if I had built a computing machine, built an IBM tabulator. I guessed how I would have built it and talked to the machine in that language, in order to fool the machine into doing the process which I wanted done. And I just poured that data in and it came out just as I wanted it, and it all succeeded and that's the way I did that job.

The thought experiment has its limits concerning the investigation of an embryonic computer architecture layout. This convinced him to reach another stage of conception, working on his own prototype. Atanasoff describes his beginning with Clifford E. Berry as follows:

> Our first effort was to try to prove the feasibility of the new methods of computing I had devised using theory only. At this point, theory would not do; we had to bring the art into physical being (Atanasoff, 1984: 241).

By 1939, he believed the time had come to propose his own solution to the calculating issue he sets to himself. Atanasoff (Smithsonian oral archives, 1969: 11) recalls:

> I was a theoretical physicist and this problem of analyzing complex spectra was very much before people at that time. So the problem was there, and the pressures of the problem were there. And I, of course, had the background in the machine and the familiarity with it and the two came together at that time.

Atanasoff started the building of a small machine of relatively modest planning[8] (see fig.1). He recalls (1984) to design a computer from a set of principles. Those principles results from his past theoretical and applied experience with the confrontation of his problem of calculation with the available machine he investigated. His prototype is based on the following set of principles:

- Electricity and electronics (not mechanical methods)
- Binary numbers internally
- Separate memory made with capacitors, (refreshed to maintain 0 or 1 state: regeneration)
- Direct 0-1 logic operations (not enumeration).

I suggest one can see those principles at work in Atanasoff's prototype if we understanding the role they play in (i) the physics of vacuum tubes for this prototype control units, (ii) the physics of the dielectric constant and the use of capacitors for computing memory and (iii) Atanasoff's working of a variant of Gauss Elimination procedures as ABC's algorithmic method to proceed with partial differential equations (Alice Burks, 2003: 36). Atanasoff's problem for representing the operation of a non-linear differential equation into a prototype required Clifford Berry's engineering skills

(Berry, 1986). Atanasoff's prototype was built to perform linear equations up to 30 unknown. This poses long-standing problems in terms of data processing and memory. Concerning data processing, Atanasoff and Berry did not possess a standard for the location of data and the transfer of instruction. Today, all data are processed in binary code by the processor and translated at different levels (compiler/assembler) between the interfaces (any programs written by the programmer) and its execution by the processor. In this prototype, none of the data are manipulated from start to finish in binary code. The initial input of data is decimal. The arithmetic is performed by direct instruction through the button and switches of the control panel. The data are written on decimal cards and read by a standard IBM decimal reader. There is an intermediary storage of results done on binary cards. Those cards comprise 30 binary numbers (words), each of 50 digits long (bits) and can contain three times more information than the decimal cards. In terms of output, since the operator has transferred decimal into binary number, the final results are punched on binary cards. The writing and reading devices requires synchronisation of electronic values to get reliable results.

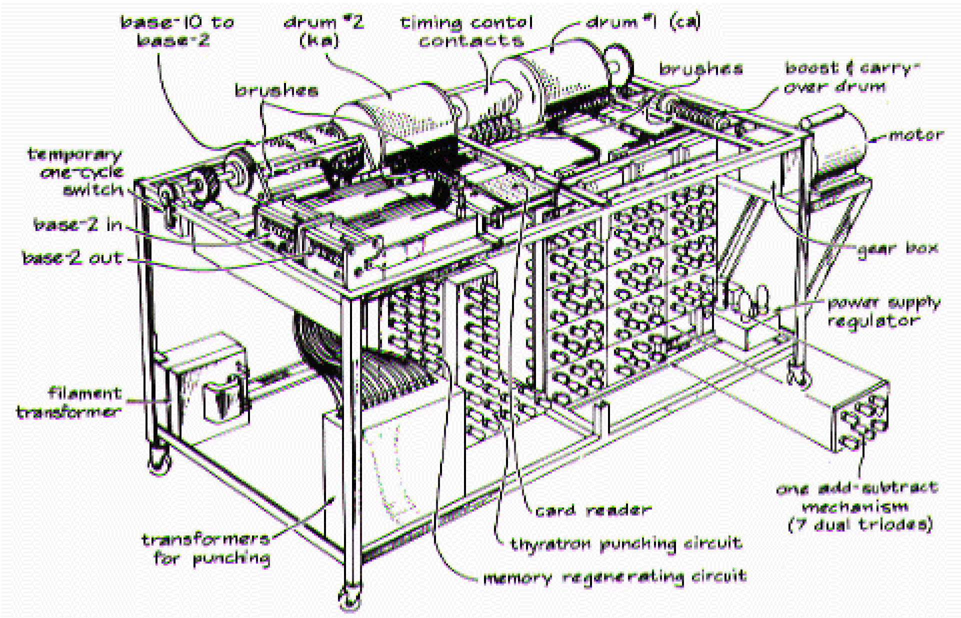

Figure 3: The Atanasoff-Berry computer prototype as reconstructed by John Gustafson and his teams at Ames Laboratory, Department of Energy, Ames, Iowa, USA. (Picture courtesy from Gustafson).

Concerning the memory, Atanasoff and Berry had to find a way to retain the data that proceeded through the vacuum tubes in some kind of memory. They devised to build capacitors (at the time called “memory condensers”) retaining information. To do that, they built two clusters of capacitors filling two rotating drums. The drums constituted the memory of the computer. Each of the drums is made of 50 rows of 30 contacts. In computer terms, the memory of one drum was 30 words by 50 bits, i.e. 1500 bits of information. To maintain the information, the capacitors contained in each drums are coupled with a system that holds the electric charge. John Gustafson’s team had recovered crucial technical information in reconstructing the ABC. Thanks to their reconstruction, one can actually say that during the period from 1938 to 1942, John Atanasoff and his graduate student Clifford Berry worked out the conceptual problem of computing linear equations through their engineering work. The insights from this process helped them to design a prototypic version of a computer processor[9].

This detailed description of Atanasoff’s design of an early computer encompasses the scientific characteristics of puzzle-solving (Kuhn, 1977), implying the share of criteria to determine the state of art’s questions (William, 2000). The contingencies regarding the design and assembly of the machine brings forward additional issues related to the availability and access to technological toolings. In this sense, Atanasoff’s prototype is participating to the growing stock of technical knowledge but cannot directly be traced back to uniform initial conditions (Arthur, 1989: 116-131; Rosenberg, 1994: 10). During those years, at the early stage of computing, the combination of scientific questions and non-standardised solutions in computer architecture are brought together in an opportunistic manner, i.e. whereby the unfolding sequence of events is driven by forward looking options. Optimism for further machines' development can be tempered or stimulated by similar endeavours. Following Schmookler's model, we will see, in the following part, how a competitive environment for computing technology emerges. It will provide a means to evaluate Atanasoff's work in relationship to it.

4. Number skilled in the art of computing in the 1930s

As in other technologies, computer does not make exception to the fact that "in the early stages of a technology history, there usually are a number of competing variants or even competing paradigms" (Dosi & Nelson 2010: 93). The issue of dominant design is certainly the outcome of the competing variant of computer. The technical challenge of the emergence of a dominant design equals to know how computer machine architecture looks like? This is very much the re-enactment of Babbage's challenge, i.e. translating the calculus into machine design. Since in the 1930´s, the conditions were favourable for several Babbage to emerge, it raised a question of the economics of invention. If many came to tackle the early computer architecture issue, the competition between scientists would render unlikely to pursue long terms research and development goals on the basis of single-minded intellectual pursuit. In other words, the progress of computer knowledge in general cannot be based on the continual supply of overtime labor. Machlup (1962: 143 & 146-7) indicates that the "supply of invention" can be understood as an "hypothetical variations in the flow of new inventions becoming available for eventual industrial application in response to variations in the compensation society offers to those who undertake the production of inventions." I schematically identify Machlups' definition of the supply of invention as the total effort devoted to the search for inventions as the "number skilled in the art of computing" defined in the following Schmookler's graph. In his graph (fig. 2 below), I selected the grey area to show that the number of technologists' skilled in the art of computing implies the condition of the existence of a "discipline" as well as competition. Schmookler's paths outlined in fig. 1 & fig. 2 are useful in showing the difference between: (1) the technologist being commitment to transform certain materials into products with the help of equipment. In Machlup's word (1962: 158), the "inventor starts with technology, applies technology and ends up with technology." And (2) the constitution of a market for technology implying competition. This market for technology exists before the commercial market whereby their combined input will move toward a diminishing return of exploitation. At this stage, competition can be defined as the number of people skilled in the art of computing between 1930-1946, whose supply of invention will be evaluated in terms of expects cost and profit by themselves or by others.

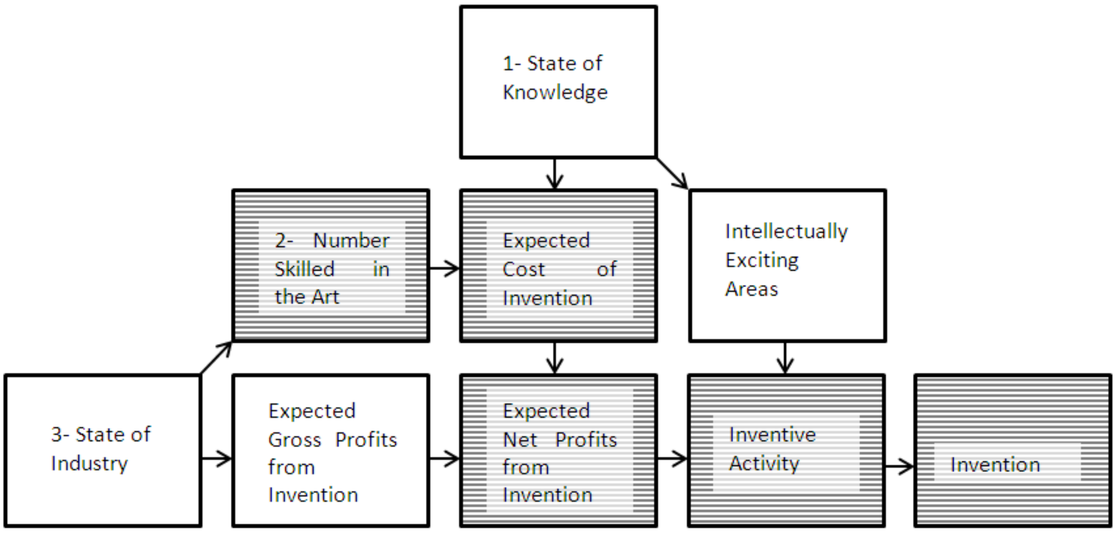

Figure 4: Schmookler's determinant of industrial invention (1962). The darker area is identifying the state of all the computer scientists' knowledge in the 1930s. The arrows signify "determines".

The 1930s saw the emergence of a number of creative individuals in electronic calculation. But before being organised so that their inventive input turned into an inventive output, those individuals were loosely connected to each other's. They carried out separately a variety of research projects on early prototypical computers. Ceruzzi (1997: 5) considers 1935 to 1955 as 'a prologue to the story' of computer leading toward the emergence of the stored program computer. Different disciplines such as electrical engineering, statistics, military planning and strategy and the natural sciences, especially physics, expressed a common need to carry out calculation of large non-linear equations. In the early days of computing, few scientists like Howard Aiken (Copeland, 2004) went through the difficulties of collaborating with companies to build a machine. One needs to remember that institutional grants[10] did not exist to support R&D in computing since it was a becoming field. Due to the uncertainty related to its novelty and the upfront development cost, R&D in computing depended on exceptionally receptive institutional financial backup.

During the 1930s and 1940s diverse areas of science and technology saw the emergence of larger numbers of inventors. In his scholarly overview of machines, Ceruzzi (1997) shows that developers are motivated by diverse issues in science such as L. J. Comrie and W. Eckert working on their punch card equipment, related to contractual scientific services such as IBM delivering the Abderdeen Relay Calculator for the US Army, or engineering-specific issues such as Northrop Aircraft constructing a Card Programmed Calculator for engineering applications. In the 1930s, the decision to build a prototype in order to solve larger calculations prohibitive of normal human methods was based on a concern shared by many scientists of the time[11]. Independently of John Atanasoff ([1940], 1973), Howard Aiken (Cohen, 2000), George Stibitz (1982), John Mauchly ([1942] 1973: 329) expressed a very similar concern reflecting the expansion of application in mathematics but also physics, biology and statistics. In G. Stibitz's terms:

‘For some years … need has been felt for a computing machine which would relieve the operator of the numerous details involved in complex computations’.

In 1937, Howard Aiken worked on very similar problems than John Atanasoff. Although Aiken mainly dealt with the solving of non-linear differential equations, he conceived his problem in industrial terms. He worked actively to find industrial collaborators to construct a machine that would mechanise the process (Cohen, 2000). He wrote up the technological specifications in terms of machine logic, mathematical operations and general architecture and contacted companies capable of building it. He obtained an interview with the director of research of the Monroe Calculating Machine Company, George C. Chase. Cohen (2000: 110) reported Aiken having said to George C. Chase that: ‘certain branches of science had reached a barrier that could not be passed until means could be found to solve mathematical problems too large to be undertaken with the then-known computing equipment.’ Chase could not bring Aiken’s proposal further up to the firm’s hierarchy since the management did not want to take the risk to go into production. Following Chase’s advice, Aiken contacted, James W. Bryce, IBM’s chief engineer to develop what would later become the IBM Automatic Sequence Controlled Calculator (ASCC, also known as Harvard Mark I). From 1937 to 1941, Howard Aiken developed a mechanical automatic calculating machine similar to the Babbage machine. Aiken’s approach to development integrated an entrepreneurial opportunism taking into account commercial and industrial realities. His approach paid off. In the beginning of the 1940s, he started developing the Mark I with IBM engineering and financial support. The Mark I was an electrically powered mechanical moving parts computer to perform calculation. Howard Aiken developed his design ideas leading to the Mark I with the problem of solving scientific tables’ calculation[12].

Atanasoff's craftsmanship approach to the problem of calculation within the area of thermodynamics, the subsequent construction of the prototype as its scientific and technical extension shows inventive advancement (Atanasoff's computer prototype is a very leap outside thermodynamics) and its limits. Atanasoff's prototype became a practical reality thanks to Clifford Berry's engineering skills. Its development was also held back due to its workshop set-up, the rarity of high tech components, the lack of sustained research project funding, the precariousness of the Iowa State College's financial support and its amateurish patent policies of the time. Atanasoff's embryonic and mainly *ad hoc* environment of research and development did not offer the continuity and development manpower necessary to transform his invention input into useful output[13].

At the time, there was reason to believe that Atanasoff did not perceive his work on the computer as an active participation in the foundation of computer science. He did not actively pursue contact with engineers who were working exclusively on computer machines[14]. Atanasoff's story shows that his context to supply an invention leading to early computing was sensitive to the limits of techno-scientific paradigm (Dosi, 1982: 152; Nelson & Winter, 1977, 1982) he worked with[15]. As such, the professional network he constituted in applied physics and computing delimits the contour of his career. Therefore, his outlook on his early machine was not opportunistic toward an entrepreneurial solution within an emergent industry. It partly explains why Atanasoff did not develop a close professional association with the Aberdeen Proving Ground research facilities in Philadelphia neither through his contacts with John Mauchly[16] nor with its director, Hermann H. Zornig. Atanasoff's professional opportunities and choice shows also that individual endeavour have their limit for bringing a critical mass of invention to the point where a market for that invention exists. In other words, the scale of research matters and I will show that institution of engineering worked as intermediary organisations toward the coordination of, at least, a work force in computing.

5. Reducing uncertainty in inventive activities: corporate, university research facilities and the military

Schmookler's graph following the number skilled in the art implied a problem of coordination of knowledge in the supply of invention. Dosi & Nelson (2010: 64) show that "at any time there generally are a wide variety of efforts going on to advance the technology, which to some extent are in competition with each other, as well as with the prevailing practices. The winners and losers in this competition are determined to a good extent through some *ex post* selection mechanisms. At no instance the interpretation of the process gains much by trying to rationalise it either in terms of consistent "gambles" by forward-looking players or by efficient "market processing" over *ex ante* blind ones." Knowledge frontier threshold requires large inventive work force providing both sufficient specialists' division of labor and knowledge cross-fertilisation.

Between 1930 to 1946, computing became a new area of research, development and mainly experimentation. New technological solutions depended directly upon the aggregated labor effort available, the amount of known problems, the available equipment of existing technology and the technological advances one can expect given those factors of inventive production. Let us consider two ex-post concentration mechanisms who played a role to coordinate or defect factors used for inventive production: 1- a density of knowledge, skills and routines organised around US Army funded research laboratories in preparation of the second world war (creating a network of well-connected inventors in a “A” team such as Aberdeen, Maryland and Endicott, New York) and 2- inventor isolated from optimal conditions for innovation (such as Ames, Iowa where Atanasoff had to deal with private firms and his own university un-advantageous patent policies for protecting his intellectual property or war condition in Berlin, Germany for Zuse’s Z1 computer).

First, let us consider the emergence of specialised laboratories. They may be understood as an early step in the organisation of a technological regime where research program, university training and regulatory structures support and constraint early computing developments. In 1938, Zorning’s laboratory (in Aberdeen, Maryland) became the Ballistic Research laboratory. It started a collaboration with the Moore School of Electrical Engineering, University of Pennsylvania, in Philadelphia. Major Paul Gillon densified computer capabilities of the laboratory by taking over the Moore School of Electrical Engineering’s differential analyser (which is an electromechanical calculator). The Moore School of Engineering with its new research facility was designed for handling computing facilities related to WWII. They created the ESMWT program (Engineering, Science, Management, War Training) to supply the large scale man-power[17] to ballistic computation. It is only later that commercial ventures, most notably IBM[18], would be associated to the further development of computer machines. As early as 1935, the US Army conceived and created large research organisations. Contrary of Europe where research institution were mainly universities long founded on religious and semi-secular traditions[19], the early twentieth century US R&D facilities worked under the managerial ethos of engineers. Its effects are largely perceivable in the emerging computing industry. For example, Oswald Veblen[20] provided essential guidelines for financial and organisational issues in ballistic research and development throughout the second world war. Under his supervision, the laboratory built the density of knowledge necessary to consider having an inventive output through the constitution of large teams of scientists in diverse fields of mathematics, physics, astrophysics, astronomy and physical chemistry organised around an advisory committee of leading American scientists.

The war effort provided the context to organise inventive input into institutional research facilities. From 1938 to 1945[21] we can see thanks to John H. Giese's statistics of research budget (see fig. 4 below) the role that war investment played toward R&D in computing. From 1937, the capital influx provided the Ballistic Research Laboratory with the means to organise a complete and integrated system of research around analogue and digital means of computation for firing and bombing tables.

Fiscal periods	**All Purpose allocation / per year**	**R&D allocation / per year**	**Remarks**
1923-28	6 M USD	1 M USD	1920 budget cut – recession. Declined every year.
1928-37	6 M USD	1 M USD	Around the same level
1937	17 M USD	Lower than 2 M USD	Increase due to the European situation
1940	177 M USD	Lower than 2 M USD	

Figure 5: Source: Herman H. Goldstine (1972: 129). From Ballistic Research Laboratory, 'Ballisticians in War and Peace,' unpublished manuscript kindly made available by Dr. John H. Giese, Chief of the Applied Mathematics Division of the Ballistic Research Laboratories.

From 1935, the research division of Ballistic Research Laboratory had large teams including around 35 researchers who performed their work with a budget of 1 million dollars per year until 1937. The supply of scientific knowledge increased and remains stable. Physical capital assets scaled up dramatically with the construction of higher capability machines (all purpose allocation almost tripling from 1936 to 1937 and multiplied by 100 from 1942). Since 1935, the research division increased its technical capability by implementing incremental changes on experimental machines. They acquired a copy of the Bush differential analyser[22] for calculation means. In 1940, a group of researchers under John Grist Brainerd and Cornelius J. Weygandt's supervision developed the arithmetic capability of the Bush differential analyser by replacing its mechanical torque amplifier by a digital one. Around 1941-2, Leslie E. Simon, Hermann H. Zornig and Major Paul N. Gillon worked to improve the input unit of the machine approaching IBM[23] to adapt their punch card system. In 1943, the organisation scale up research and development on computing even further[24] opening up the era of mainframe computers after 1945. The result of the organisation of R&D did not eliminate or reduce the ability of commercial computing to emerge but provide the inventive and managerial ability to engage in endeavour having future profitability. In other words, private firms decided to capitalise on technological development when the expected cost of invention supported by public institution could be transformed into expected net profit. This opportunistic and positive complementarity was exploited by private firms, such as IBM and NCR.

Secondly, let us consider for a moment how difficult for an individual researcher it was to be outside the US army organisation facilities, private research labs or well-organised university systems to protect its own intellectual property at the early stage of computer design. To exemplify it, I will review two difficulties Atanasoff's encountered as a single inventor in regard to intellectual property rights: 1- with IBM as his supplier of specialised equipment and 2- with Iowa State College's patent policies. Being in an early stage of invention is not equivalent to being first in the market of innovative ideas

(ideas ready to be exploited into a commercial endeavour.) In the following sections, I show that the computer's inventor had to deal with two unrelated dimensions of his work. On the scientific side, not all technical colleges were equally equipped with means to handle technological patents. On the technology side, the manufacturing suppliers of specialised equipment also played by the rules of their competitive positioning in their market. Both turned out to be sources of unsolvable issues.

In 1942, IBM Endicott's laboratory manager of the electronic division, G. H. Armstrong knew that many crucial ideas in computing would be coming from people outside the company. IBM policies[25] concerning technology development were to follow a strong patent policy by securing as systematically as possible its acquisition. Patent acquisition was a secure way to venture into technological domain by avoiding the risky and costly process of engineering. Armstrong learned about Atanasoff thanks to an order he placed for a specific kind of contact brush for his prototype. Armstrong initiated a contact with him. According to Emerson W. Pugh (1995: 86) G. H. Armstrong addressed Atanasoff along those lines[26]: 'When your development work has proceeded to a point where you fell that it is proper for representatives of our Company to look over your machine, we would appreciate an opportunity to do so. Naturally, we do not wish to accept any confidential disclosures.' According to the IBM business plan, it was crucial to concentrate development on new products without risking the company's assets. IBM knew it was impossible to make a profit in a domain where there was a limited market niche and a very narrow client network. Through James Bryce, the director of the Patent Development Department, IBM developed an active patent policy strategy of technological development and acquisition. The idea was to secure IBM as the owner of key components when related technological development would mature into consumable market product. It is understandable that from Atanasoff's scientific perspective, IBM's approach looked rather aggressively dispossessing rather than scientifically incremental and personally inclusive. IBM's business approach was pragmatic, conservative in regard of market prediction and competitive in regard of technological development. James Bryce, himself, patented an incredible number of technologies[27]. One finds 244 patents for tabulators and time recorders during the period 1911-1950 under his name alone. During the period 1936-40, he registered under his name 44 patents for IBM. From 1940 till 1942, 6 patents[28] on early electronic computing circuits had been registered by inventors working for IBM, NCR and RCA respectively. Regarding specifically the context of technological development, Atanasoff's work could not easily compete and successfully emerge as a unique design in calculating devices.

In July 1941, Atanasoff started to proceed with the patent of his computer (renamed later the ABC – the Atanasoff-Berry-Computer[29]) at his home institution, the Iowa State College (ISC). The Iowa State College Research Foundation (ISCRF) supported him in his choice of Chicago's patent attorney Richard R. Trexler. Unfortunately, the president of ISC, himself, Charles E. Friley, interfered with the patent process when he saw Atanasoff was awarded a grant of 5330 dollars by a private foundation (the Research Corporation, foundation of Howard Poillon). Negotiations between the president of ISC and Atanasoff ensued concerning the right to depose a patent exclusively with ISCRF. The university wanted also to take 90% of the grant for university expenses and leave 10% to Atanasoff. Atanasoff engaged in negotiation with his home university to finally settle down with an agreement. The ISCRF will have the exclusive right for the ABC patent and the managerial right to spend the money. The ISCRF paid half the cost of the computer and engaged to reimburse the second half of the cost to Atanasoff when all final expenses are paid. The aftermath of this internal political struggle at his home university discouraged Atanasoff to pursue patenting his machine.

Atanasoff's story shows that individual protection of intellectual property right represents a step into the ability to give birth to an invention by potentially figuring in the procedures of supplier of technology. I have shown that, in the stage of the densification of invention, the suppliers of technology prove to be essential partners in technological inventions. This indicates strongly that the alignment of intellectual property with the competitive condition of the market of technology is a pre-requisite, not an option, in the development of technological invention.

Conclusion

The inventive input characterising the early years of US computing (roughly 1930 to 1946) reflects adjustments between unrelated type and sources of technological knowledge. The problem this paper addressed is how the supply of invention in early computing forces us to address the coordination of a self-emerging scientific production with suppliers of technology, the early competitive condition of computer inventions to see gradually the need for standards and the role of institution to organise some supply of it. Hayek refers to this problem as the "division of knowledge" and considers it as "the central problem of economics as a social science". He points out that assuming perfect competition presumes perfect knowledge between actors. In emerging technological fields, this issue is important. It requires taking social order as a serious topic for economics. This historiographical study refined our understanding of invention by articulating its pre-economic condition of coming about with contingent conditions of a technical field to emerge. It has shown that imperfect division of knowledge starts with (a) an work-in-progress relationship between scientific puzzle-solving and technological tooling to solve it; (b) competitive condition of the market of technology whereby other actors may have found a better configuration for solving the relation (a) mentioned above; (c) a conditional alignment between the invention and the market positioning of technological suppliers. The dynamics of technological change is made visible through frictions inventors encounter when orienting themselves toward their engineering procedures or standards which remained to-be defined. Between 1930-1945, the emergence of computing is an unplanned coordination of invention input through sets of single inventions and similar endeavour engaged by many geographically scattered inventors around the country. At that point, inventors are orienting their attention toward a thematic outcome: a technological solution to large linear equations. Their inventive horizon, which Schütz calls (1970: 5) a "sedimentation of previously experienced events" become a rather complex experiential framework due to the following demands technology puts on the inventor:

- the effort in invention needs to be pursued not uniquely in the form of a scientific paradigm (Kuhn, 1962) but con-substantively with useful technological outcome.
- The constitution of a market for new technology is competitive in the specific sense in which computer technology is the resulting emergence of competitors who have succeeded in solving the alignment between scientific puzzle and technological tooling.
- The best placed competitors found support in the modern academic research departments. The ad hoc US educational facilities do not provide a substitute to the market of new computing technology but an experimental ground to groom the probability of further inventive output.

- A computing paradigms are not in place, notably around computer architecture issues. Debates between different actors about the legitimate methods, problems, and standards of computing solution will take place. When it is the case, those debates involve deep disagreement partly because the issues involved are not uniquely scientific but embeds people's own position in an industry.

Early computing history investigated the condition for the transformation of an inventive input into an output useful for production. Schmookler's model is useful in framing the question of invention for computing. From his three essential components: 1- a stage of scientific knowledge enacted by individual scientists, 2- the competitive market of such invention populated with other scientists presumably tackling similar questions and 3- the industrial condition to transform assets into expected net profit, I show that the interaction of the two first steps interrogates the condition of emergence of a new technology and is better investigated with historiographical means. This study contributes precisely to the literature on technological change on that aspect. It shows that interaction between individual incentives and competitive alignment within a discipline are accidentally made of conflicts, but essentially involve continuous and costly adjustments[30].

Funding:

This work was supported by the STINT foundation (the Swedish Foundation for International Cooperation in Research and Higher Education), [grant number: KU2003 4073].

Acknowledgements:

Thanks to the STINT foundation grant for allowing me to spend a three month research period at Georgia Tech, USA. I have received key support from Kenneth Knoespel, Jay Bolter at Georgia Institute of Technology, USA; my wife Maria Engberg, Malmö University, Sweden; Charlie Karlsson, Jönköping International Business School, Sweden; Martin Andersson, Circle, Lund, Sweden; Michael Lynch, Cornell University, USA and Wes Sharrock, the University of Manchester, UK. I thanks the participants at the seminar at the department of Industrial Economics and Management for their comments, suggestions and questions.

References:

Arthur, B. (1989) "Competing technologies, increasing returns and lock-in by historical small events" *Economic Journal*, 99: 116-131.

Aspray W. (1990a) *John Von Neumann and the Origins of Computer Technology*, MIT Press, Cambridge, MA.

Aspray, W. (1990b) 'The stored program concept', *IEEE Spectrum*, Sep 1990 vol. 27, issue 9: 51.

Aspray, W. (2000) 'Was Early Entry a Competitive Advantage? *IEEE Annals of the History of Computing*, vol. 22, no. 3: 42-87.

Aspray, W. & Williams, B. (1994) 'Arming American Scientists: NSF and the Provision of scientific Computing Facilities for University, 1950-1973', *IEEE Annals of the History of Computing*, vol. 16, no 4: 60-74.

Atanasoff, J. V. & Brandt A. E. (1936) 'Application of Punched Card Equipment to the Analysis of Complex Spectra', *Journal of the Optical Society of America*, vol. 26, no. 2: 83-88.

Atanasoff J. V. ([1940], 1973) 'Computing Machine for the Solution of Large Systems of Linear Algebraic Equations', in B. Randell (ed.) *The Origins of Digital Computers*, Springer-Verlag, Berlin: 305-25.

Atanasoff J. V. (1984) 'Advent of Electronic Digital Computing', *IEEE Annals of the History of Computing*, 6: 229-82.

Berry, J. R. (1986) 'Clifford Edward Berry, 1918-1963: His role in Early Computers', *IEEE Annals of the History of Computing*, vol. 8, no. 4, October: 361-369.

Bresnahan, T. F. (2012) "Generality, Recombination and Reuse", in J. Lerner & S. Stern (eds.) *The rate and direction of inventive activity revisited*, National Bureau of Eocnomic Research, The University of Chicago Press, Chicago: 611-661.

Bush, V. (October 1931). "The differential analyzer. A new machine for solving differential equations". *Journal of the Franklin Institute* **212** (4): 447–488.

Burks A. W. (2003) *Who Invented the Computer? The Legal Battle that Changed Computing History*, Prometheus Books, New York.

Burks, A. W., Goldstine, H. H., Von Neumann, J. ([1946], 1987) 'Preliminary Discussion of the Logical Design of an Electronic Computing Instrument', in *Papers of John von Neumann*, W. Aspray and A. Burks (eds.), The MIT press, Cambridge, MA: 97-146.

Cohen, B. I. (1988) 'Babbage and Aiken', *IEEE Annals of the History of Computing*, vol. 10, no. 3, Jul-Sept.: 171-193.

Cohen, B. I. (2000) 'Howard Aiken and the Dawn of the Computer Age', Raúl Rojas & Ulf Hashagen (eds.), *The First Computers: History and Architectures*, The MIT Press, Cambridge, MA: 107-120.

Copeland, J. B. (2004) 'Unfair to Aiken', *IEEE Annals of the History of Computing*, vol. 26, no. 4 :35-7.

Cortada, J. W. (1993) *Before the Computer: IBM, NCR, Burroughs and Remington Rand and the Industry they created, 1865-1956*, Princeton University Press, Princeton, N.J.

Ceruzzi, P. E. (1983) *Reckoners: The Prehistory of the Digital Computer, from Relays to the Stored Program Concept, 1935-1945*, Greenwood Publishing Group Inc. Westport, CT.

Ceruzzi, P. E. (1988) 'Electronic Technology and Computer Science, 1940-1975: A Co-evolution', *IEEE Annals of the History of Computing*, vol. 10, no. 4: 257-275.

Ceruzzi, P. E. (1997) 'Crossing the divide: architectural issues and the emergence of the stored program computer, 1935-1955', *IEEE Annals of the History of Computing*, vol. 19, Issue: 1, Jan-Mar: 5-12.

Clarance Larson collection, (1985) Interview with John V. Atanasoff [Online], Recorded March 19, 1985. Available at: https://ieeetv.ieee.org/player/html/viewer?dl=#larson-collection-interview-with-john-v-atanasoff [8 Apr.2014].

David, P. (2001) "Path dependence, its critics and the quest for 'historical economics', in Garrouste, P. Ioannides, S. (eds.) *Evolution and Path Dependence in Economic Ideas: Past and Present*, Edward Elgar Publishing, Cheltenham, UK.

Dosi, G. (1982) "Technological paradigms and technological trajectories", *Research Policy*, 11: 147-162.

Dosi, G.; Nelson, R.R. (1994) "An introduction to evolutionary theories in economics", *Journal of evolutionary economics*, 4: 153-172.

Dosi, G.; Nelson, R.R. (2010) "Technical change and industrial dynamics as evolutionary processes", in Bronwyn H. Hall & Nathan Rosenberg (eds.) *Handbook of the Economics of Innovation, vol. 1*, Elsevier, Amsterdam: 51-127.

Goldstine, H. (1972) *The Computer: From Pascal to von Neumann*, Princeton university press, Princeton.

Goldstine, H. (1992) 'Computer at the University of Pennsylvania's Moore School, 1943-1946', *Proceedings of the American Philosophical Society*, vol. 136, no. 1.

Goldstine, H., Goldstine, A. ([1946], 1982). “The Electronic Numerical Integrator and Computer (ENIAC)”, *The Origins of Digital Computers: Selected Papers*. New York: Springer-Verlag, 359-373.

Grier, D. A. (2000) ‘Agricultural Computing and the Context for John Atanasoff’, *IEEE Annals of the History of Computing*, vol. 22, no. 1 :48-61.

Gustafson, J. (2000) ‘Reconstruction of the Atanasoff-Berry Computer,’ in Raúl Rojas & Ulf Hashagen (eds.), *The First Computers: History and Architectures*, The MIT Press, Cambridge, MA: 91-106.

Hayek, F. A. ([1936] 1958) “Economics and knowledge” in *Individualism and Economic Order*, The University of Chicago Press, Chicago: 33-56.

Kuhn T. (1962) *The Structure of Scientific Revolutions,* The University of Chicago Press, Chicago.

Kuhn T. (1977) “The relations between the history and the philosophy of science” and “Logic of Dicovery or Psychology of Research”, *The Essential Tension: selected studies in scientific tradition and change*, The University of Chicago Press, Chicago: 3-20 and 266-292.

Kuznets, S. (1962), “Inventive activity: problems of definition and measurement.” In *The rate and direction of inventive activity: economic and social factors*: National Bureau of Economic Research, Princeton University Press, Princeton: 19-43.

Light, J. S. (1999) ‘When Computers Were Women’, *Technology and Culture*, vol. 40, no. 3: 455-483.

Machlup, F. (1962), “Supply of inventors and inventions”. In *The rate and direction of inventive activity: economic and social factors*: National Bureau of Economic Research, Princeton University Press, Princeton: 143-167.

Mahoney, M. S. (1988) ‘The history of computing in the history of technology’, *IEEE Annals of the history of Computing*, vol. 10, no. 2: 113-125.

Malerba, F.; Nelson, R. R.; Orsenigo L.; Winter, S. (1999) "'History-friendly' models of industry evolution: the computer Industry", *Industrial and corporate change*, vol. 8, no 1: 3-40.

Marcus, M. & Akera A. (1996) 'Exploring the Architecture of an Early Machine: The Historical Relevance of the ENIAC Machine Architecture, *IEEE Annals of the History of Computing*, vol. 18, no. 1: 17-24.

Mauchly J. W. ([1942] 1973) 'The use of high speed vacuum tube devices for calculating' in Randell (ed.) *The Origins of Digital Computers*, Springer-Verlag, Berlin: 329-32.

Mazzucato, M. (2014) *The entrepreneurial state: debunking public vs. private sector myths*, Anthem Press, New York.

Mokyr, J. (1990) "chapter 11: Evolution and the dynamics of technological change", in *The lever of riches: technological creativity and economic progress*, Oxford University Press, Oxford: 273-300.

Nelson, R. R. (1959) "The economics of invention: a survey of the literature", *The Journal of Business*, vol. 32, no. 2: 101-127.

Nelson, R. R. (1962) "Introduction" In *The rate and direction of inventive activity: economic and social factors*: National Bureau of Economic Research, Princeton University Press, Princeton: 3-16.

Nelson, R. R. (1994) "The Co-evolution of Technology, Industrial Structure, and Supporting Institutions", *Industrial and Corporate Change*, 3 (1): 47-63.

Nelson, R. R. (1995) "Co-evolution of industry structure, tchnology and supporting institutions and the making of comparative advantage", *International Journal of the Economics of Business*, vol. 2, no 2: 171-184.

Nelson, R. R. (2007) "Understanding economic growth as the central task of economic analysis", in F. Malerba, S. Brusoni (eds.) *Perspectives on innovation*, Cambridge University Press, Cambridge: 27-41.

Nelson, R. R. (2008) "Factos affecting the power of technological paradigms", *Industrial and corporate change*, vol. 17, no. 3: 485-497.

Nelson, R. R.; Phelps E. S. (1966) “Investment in human, technological diffusion and economic growth”, *The American Economic Review*, vol. 56, no. ½: 69-75.

Nelson, R. R.; Winter S. G. (1977) “In search of useful theory of innovation”, Research Policy, 7: 36-76.

Nelson, R. R.; Winter S. G. (1982) *An evolutionary theory of economic change*, Belknap Harvard.

Nelson, R. R.; Winter S. G.; Shuette H. L. (1976) “Technical change in an evolutionary model”, *The Quarterly Journal of Economics*, vol. 90, no. 1,: 90-118.

Nordhaus, W. D. (2007) “Two centuries of productivity growth in computing”, *Journal of Economic History,* 67(1): 128-159.

Phelps, B. E. (1980) ‘Early Electronic Computer developments at IBM’, *Annals of the History of Computing*, 2: 253-67.

Pugh, E. W. (1995) *Building IBM: shaping an industry and its technology*, The MIT press, Cambridge, MA.

Rosenberg, N. (1982) *Inside the black box: technology and economics*. Cambridge University Press: Cambridge.

Rosenberg, N. (1994) *Exploring the black box: technology, economics and history*. Cambridge University Press: Cambridge.

Rosenberg, N. (2000) *Schumpeter and the endogeneity of technology: some american perspectives*, Routledge, London.

Rosenberg, N., Nelson, R. R. (1994) “American universities and technical advance in industry”, *Research policy*, 23 (3): 323-348.

Smithsonian National Museum of American History, *Computer Oral History Collection*, Atanasoff J. V. (1969-73; 1977), Lemelson Center for the Study of Invention and Innovation, Washington DC.

Schmookler, J. (1962), “Changes in industry and in the stage of knowledge as determinants of industrial invention”. In *The rate and direction of inventive activity: economic and social* *factors*: National Bureau of Economic Research, Princeton University Press, Princeton: 195-232.

Schütz, A. (1970) *Reflections on the problem of relevance,* Ricard M. Zaner (ed.), Yale University Press, New Haven.

Stern, N. (1981) *From ENIAC to UNIVAC: an appreaisal of the Eckert-Mauchely computers*, History of computing series, Digital Press, Bedford, MA.

Stibitz G. R. (1982) "Automatic computing machinery". *Annals of History of Computing* 4(2) :140-142.

Tausig F. W. (1925) *Inventors and money-makers*, MacMillan: New York.

Veblen T. (1898) "The instinct of workmanship and the irksomeness of labour", *American Journal of Sociology*, september 1898: 187-201.

Van den Ende, J.; Dolfsma, W. (2005) "Technology-push, demand-pull and the shaping of technological paradigms- patterns in the development of computing technology", *Journal of Evolutionary Economics*, 15 (1): 83-99.

Von Neumann J. ([1945], 1993) 'First draft of a Report on the EDVAC', University of Pennsylvania, Moore School of Electrical Engineering, June 30, 1945. Reprinted in *IEEE Annals of the History of Computing*, vol. 15, no.4: 27-75.

Williams, M. R. (2000) 'A Preview of Things to Come: Some Remarks on the First Generation of Computers', Raúl Rojas & Ulf Hashagen (eds.), *The First Computers: History and Architectures*, The MIT Press, Cambridge, MA: 1-13.

---

[1] The ENIAC (Electronic Numerical Integrator And Computer) is considered a landmark in modern computing, i.e. the first large scale electronic general purpose computer.

[2] The historiographic work here is a kind of sociology of technical change articulating Schmookler's reflection on invention, notably the scientist's incentive, a market of inventors and finally a market of technology with richer details allowing to trace the way those elements formed an actual social structure of invention.

[3] Rosenberg (2000: 80) the combinatory technical solutions present in early computing is an open road to innovation. Adopting Bresnahan's terminlogy (2012), computing as a general purpose technology (GPS)

is a source, as a system of building technological blocks with multiple applications, of competition for invention.

[4] Atanasoff shares with the 1930s fellow scientists the same concern for larger calculation overcoming human shortcoming in calculation capabilities. Atanasoff ([1940], 1973) formulates his problem in terms of the limitation of our capacities to calculate over a certain number of unknown in an equation: ‘since an expert (human) computer takes about eight hours to solve a full set of eight equations in eight unknowns, k is about 1/64. To solve twenty equations in twenty unknowns should thus require 125 hours. (…) The solution of general systems of linear equations with a number of unknowns greater than ten is not often attempted.’

[5] A number is represented by a physical entity in the machine like a distance, an electric voltage, electric current, or air pressure.

[6] Rosenberg (2000: 48) indicates that Iowa state collegue was, with North Carolina, a strong agricultural experiment station running sophisticated statistical analysis and permitted to built prototypes to try new solutions.

[7] Grier (2000) is misleading to think that Atanasoff's main motivation was to work out agricultural statistics. In Atanasoff's view, collaboration with Brandt is useful to his research in an oblique manner, i.e. a training ground for working out the data processing architecture of the IBM punch card equipment.

[8] John Gustafson and his teams at Ames Laboratory, Department of Energy, Ames, Iowa, USA constructed a replica of the Atanasoff- Berry Computer (Gustafson, 2000: 94-5). This is a very important endeavour answering question about the computer functions such as the running of equations, the real capacity to calculate linear equations with 30 unknowns, the reliability of the processor in terms of rounding errors, the practicalities of entering the data, etc. The actual size of the computer (L: 1.5 m, H: 0,91; W: 0,91) makes it a compact machine in comparison to computer machine built at the time thanks to governmental fundings. Atanasoff's computer size itself betrays the prototypic quality of an actual workshop. See http://www.scl.ameslab.gov/ABC/ for extensive materials and details of the reconstruction.

[9] Bernard Cohen (1988: 129) mentioned Atanasoff's computer to be a proto-computer. The basic design of early computers is captured by Von Neumann (1945) ‘First Draft of a Report on the EDVAC’ explaining the key functions of a stored program machine. It comprises 5 units: (1) a central arithmetic unit, (2) a central control unit, (3) a memory unit, (4) an input and (5) output unit. The historian of

science, W. Aspray (1990a: 39-40; 1990b) precises that Von Neumann's stored-program computer specifies logical components rather than engineering precepts. See also Burks, A. W; Goldstine H. H. & Von Neumann, J. ([1946]1987).

[10] Aspray & Williams (1994) show that institutional support for early computers did not exist. For example, the US National Science Foundation dealt with grant proposals incorporating computing from 1953 onwards. From 1946, well-founded academic institutions such as Columbia, Harvard, MIT, Pennsylvania and Princeton hosted computers becoming leading computing & scientific institutions (Aspray, 2000).

[11] The possibility to solve a system of linear algebraic equations finds application in other fields than quantum physics. The computer solving such equations can be found in applied mathematics and physics (elastic rods and plates) and engineering (analysis of vibration) all having application in the industry and war machines.

[12] From the corporate's point of view, the head of IBM, Thomas Watson Sr. considered the Mark I as an IBM investment in a niche market of scientific computing. From 1938 to 1945, IBM judged rightly that computer would only be commercialised along with their secured product line such as their electromechanical card equipment.

[13] Personal choices reflects the limited perspective offered to develop futher the existing prototype. In 1942, Atanasoff ended research on his own computer in favour of career opportunities. Due to the US entering WWII, he was offered a job at the Naval Ordnance Laboratory to engage in a war research effort. The ABC computer project's main engineer, Clifford Berry, found a job in California after the completion of his PhD.

[14] Let keep in mind that John V. Atanasoff belonged to a number of prominent professional associations none of which were dealing, even later in his professional life, with computer science such as: the American Physical Society, The American Association for the Advancement of science, the American Vacuum Society, Instrument Society of America, The American Chemical Society, The American Optical Society, and worked and presented papers at the Gordon Research Conference on Instrumentation (chairman in 1959), the Max Planck Institut für Kohlenforschung, The National Bureau of Standards Symposium on Mass Spectrometry, The American Institute of Electric Engineering, the Western Spectrometry Association.

[15] Kuznet (1962: 24) provides a fine definition of invention as "a new combinations of existing knowledge in devices potentially useful in economic production and resulting from a mental performance above the average" which is assuming a connection between the demonstration of higher level of mental effort and the usefulness in economic production which is premature in regard to Atanasoff's story.

[16] John Mauchly was one of the chief engineer of the ENIAC computer with J. Presper Eckert of the University of Pennsylvania.They were assisting in its development by Robert F. Shaw (function tables), Jeffrey Chuan Chu (divider/square-rooter), Thomas Kite Sharpless (master programmer), Arthur Burks (multiplier), Harry Huskey (reader/printer) and Jack Davis (accumulators). John Mauchly paid a visit in Iowa to John V. Atanasoff in 1941 for a technical review of his machine.

[17] The university trained a large number of "computers" in ballistic computation. "Computer" was the jargon terms to refer to most exclusively women performing ballistics coputations during the war. Light (1999) provides information about the scale of the computer development endeavor. Early computer engineers such as John W. Mauchly and Arthur W. Burks received their training in electrical engineering at the Moore school. The Moore school provided itself the technical management of larger project such as the ENIAC (with chief engineers Presper Eckert and John W. Mauchly) working with up to 200 personal teams made of "computer" women both civilian and military.

[18] Since 1932, IBM had established a laboratory of research and engineering activities in Endicott, New York. IBM was not a computer company at the time but developped reliable tabulator, notably the Numeric printing tabulator in 1933 and the type 405 alphabetic counting machine in 1934 using IBM card system to tabulate and print numeric information on cards.

[19] See chapter 3 "American universities as endogeneous institutions" in Rosenberg (2000: 36-57). Rosenberg, N. & Nelson, R. R. (1994).

[20] Oswald Veblen, chief scientist of the Ballistic research lab, may be regarded as a modern architects of US research and development.

[21] From the political point of view of the organisation of science and technology, the president Theodore Roosevelt decided in June 28, 1941 to create the Office of Scientific Research and Development (OSRD). Under the direction of Vannevar Bush, the OSRD provided an environment for the ultimate exploitation of the technological and logistical superiority created as a result of the war effort to benefit other fields of scientific and technical development. In 1941, under committees such as the General Policy Group and

Military Policy Committee respectively lead by Vannevar Bush and James Conant, one sees the constitution of a scientific complex of research. It concentrates high levels of engineering resources and capital in the major universities on the east coast (Aberdeen, Philadelphia, Harvard, Cornell, Colombia) and is connected with the business world (Bernard Cohen, 1988). The OSRD activities remained hidden from the public but Roosevelt was very openly concerned with the transfer of scientific and technological experience to the civilian population.

[22] Bush (1931). Marcus & Akera (1996: 19) for work done on the differential analyser at the Moore School of Electric Engineering and the subsequent contractual relationship with the Ballistics Research Laboratory during WWII.

[23] John McPherson from IBM worked on on it at the research division of the Ballistic Research Laboratory. Around 1942, people worked on punch card machines to do ballistic calculation.

[24] They started to built the ENIAC (Electronic Numerical Integrator And Computer) started under military 'project PX'. Two engineers, J. Presper Eckert, John W. Mauchly, were in charged of the project running its first problem in december 1945.

[25] In 1935, IBM was in the office machine business. By 1956, IBM became the first computer corporation.

[26] Letter G.H. Armstrong to J.V. Atanasoff, 21 May 1942. Cited in Pugh (1995).

[27] Source: Appendix B: IBM's early patents filed on Tabulators and Times Recorders during five years periods, in Emerson W. Pugh (1995: 325) from data in the IBM patent digest of 12 February 1952. Bernard Cohen (2000: 112) mentioned that James W. Bryce was known inside IBM as 'the father engineer' honoured in 1936, on the centenary of the US patent office, one of the 'greatest living inventors'.

[28] Source: Appendix C: Early Electronic Computing Circuit Patents in Emerson W. Pugh (1995: 325) in B. E. Phelps, (1980).

[29] After Mr. Berry's death, in 1962, Atanasoff decided to rename the computer the ABC.

[30] Those adjustments define the conditions for the dissemination of technological knowledge and assume contextual restrictrions (such as secrecy, place and time dependancies).