Complexity and Prediction: The birth of computational thinking[1]

'But Thetis of the silver feet came unto the house of Hephaistos, imperishable, starlike, far seen among the dwellings of Immortals, a house of bronze, wrought by the crook-footed god himself. Him found she sweating in toil and busy about his bellows, for he was forging tripods twenty in all to stand around the wall of his stablished hall, and beneath the base of each he had set golden wheels, that of their own motion they might enter the assembly of the gods and again return unto his house, a marvel to look upon. Thus much were they finished that not yet were away from the fire, and gathered all his gear wherewith he worked into a silver chest; and with a sponge he wiped his face and hands and sturdy neck and shaggy breast, and did on his doublet, and took a stout staff and went forth limping; but there were handmaidens of gold that moved to help their lord, the semblances of living maids. In them is understanding at their hearts, in them are voice and strength, and they have skill of the immortal gods.' The Iliad, Book XVIII.

'If every tool, when ordered, or even of its own accord, could do the work that befits it … then there would be no need either of apprentices for the master workers or of slaves for the lords.' Aristotle.

'If I were to choose a patron saint for cybernetics[2]..., I should have to choose Leibniz. The philosophy of Leibniz centers around two closely related concepts – that of a universal symbolism and that of a calculus of reasoning. From these are descended the mathematical notation and the symbolic logic of the present day. Now, just as the calculus of arithmetic lends itself to a mechanization progressing through the abacus and the desk computing machine to the ultra-rapid computing machines of the present day, so the calculus ratiocinator *of Leibniz contains the germs of the* machina ratiocinatrix*, the reasoning machine. Indeed, Leibniz himself, like his predecessor Pascal, was interested in the construction of computing machines in the metal. It is therefore not in the least surprising that the same intellectual impulse which has led to the development of mathematical logic has at the same time led to the ideal or actual mechanization of processes of thought.' Norbert Wiener.*

'Over the years, the constant and most reliable support of computer science - and of science generally - has been the defense establishment. While old men in congress and parliaments would debate the allocation of a few thousand dollars, farsighted generals and admirals would not hesitate to divert substantial sums to help oddballs in Princeton, Cambridge, and Los Alamos.' Metropolis, 1976.

It is interesting to consider some historical sketches that connect different fields in computer science, physics, economics, neuroscience, and cross-disciplinary subjects such as cellular automata. Hopefully these sketches will help in trying to understand 1) contemporary discussions about complexity and prediction, and 2) new tools that are being developed such as simulations, 'agent-based models', training programmes based on the *Good Judgement Project*, and so on. Further, many contemporary debates concerning scientific, technological, economic, and political issues depend on computers - from algorithmic high frequency trading to machine intelligence and military robots - so it is interesting to consider the origins of the field. This sketch follows one on Von Neumann and economics. Von Neumann was involved in major developments in all of these fields in the 1940s. This page gives an Index of related blogs and papers. Please leave comments and corrections in the comments box.

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[1] Much of this is taken from George Dyson's *Darwin Among the Machines* and *Turing's Cathedral*.

[2] In the 1940's, Wiener christened 'the entire field of control and communication theory, whether in the machine or the animal' with the name 'cybernetics which we form from the Greek χυβερνήτης or steersman'. Ampere, in '*Essay on the Philosophy of Science, or Analytic exposition of a natural classification of human knowledge*' (1843), coined the term '*cybernetique*' for the body of knowledge which originally among the Greeks referred to the steering of a ship but which they extended to 'the art of steering in general' (Dyson, p. 6).

In Greek mythology Hephaistos gave the Cretans *Talos*, a huge mechanical statue that hurled boulders at approaching enemy ships. The Greeks possibly used steam power for mechanical devices (e.g. Archytas, a friend of Plato, reputedly built 'the Pigeon', a steam-driven model bird), Hero of Alexandria described a steam engine in the first century A.D, and we have found (but only recently understood) the amazing '[Antikythera device]' - an ancient Greek analog computer used for astronomical computations. I will not explore the debates about these ancient technologies. For the purposes of understanding how this field changed the world in the 20th century, I will start with Pascal and Leibniz.

In 17th Century Europe, the discovery of logarithms and the invention of the slide rule helped rapid progress in calculation. John Napier developed 'logarithms' (log): if we are using base ten, then the log of 10 is 1, the log of 100 is 2, the log of 1,000 is 3 and so on; i.e. 'the log of *n*' is the power to which a base number is raised to produce *n*. The first slide rule, a mechanical calculator using logarithms, was produced by William Oughtred in 1632-3.

Pascal built a primitive calculating machine in 1642-3 and Leibniz built a computer in the 1670's but they were ignored. Leibniz was the first to set down problems of information and computation in recognisably modern form, and is often quoted as an inspiration by 20th Century pioneers in computation. First, he proposed a comprehensive and exact symbolic language that could encompass all human knowledge (*characteristica universalis*). Second, he proposed a machine (*calculus ratiocinator*) to answer questions mechanically in that language.

He described the problems humans now have in resolving disputes and understanding the world and held out a promise of what his method could bring:

> 'And although learned men have long since thought of some kind of language or universal characteristic by which all concepts and things can be put into beautiful order, and with whose help different nations might communicate their thoughts and each read in his own language what another has written in his, yet no one has attempted a language or characteristic which includes at once both the arts of *discovery* and *judgement*, that is, one whose signs and characters serve the same purpose that arithmetical signs serve for numbers, and algebraic signs for quantities taken abstractly.[3] Yet it does seem that since God has bestowed these two sciences on mankind, he has sought to notify us that a far greater secret lies hidden in our understanding, of which these are but the shadows…
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> 'Once the characteristic numbers for most concepts have been set up, however, the human race will have a new kind of instrument which will increase the power of the mind much more than optical lenses strengthen the eyes and which will be as far superior to microscopes or telescopes as reason is superior to sight. The magnetic needle has brought no more help to sailors than this lodestar will bring to those who navigate the sea of experiments... But reason will be right beyond all doubt only when it is everywhere as clear and certain as only arithmetic has been until now.
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> 'Then there will be an end to that burdensome raising of objections by which one person now usually plagues another and which turns so many away from the desire to reason. When one person argues, namely, his opponent, instead of examining his argument, answers generally, thus, 'How do you know that your reason is any truer than mine? What criterion of

[3] Leibniz sought a general problem-solving method for all questions of knowledge (*ars magna*). There were two versions of the *ars magna*: the *ars inveniendi*, which finds all true scientific statements, and the *ars iudicandi*, which allows one to decide whether it is true.

> truth have you?' And if the first person persists in his argument, his hearers lack the patience to examine it. For usually many other problems have to be investigated first, and this would be the work of several weeks, following the laws of thought accepted until now. And so after much agitation, the emotions usually win out instead of reason, and we end the controversy by cutting the Gordian knot rather than untying it. This happens especially in deliberations pertaining to life, where a decision must be made; here it is given to few people to weigh the factors of expediency and inexpediency, which are often numerous on both sides, as in a balance… There is hardly anyone who could work out the entire table of pros and cons in any deliberation... And we need not be surprised that this is what has happened until now in most controversies in which the matter is not clear, that is, is not reduced to numbers.
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> 'Now, however, our characteristic will reduce the whole to numbers, so that reasons can also be weighed.' (*On the General Characteristic*)

Elsewhere he described this new language as 'a kind of *general algebra* in which all truths of reason would be reduced to a kind of calculus.'

> '… [T]his universal writing will be as easy as it is common, and will be capable of being read without any dictionary; at the same time, a fundamental knowledge of all things will be obtained. The whole of such a writing will be made of geometrical figures, as it were, and of a kind of pictures - just as the ancient Egyptians did, and the Chinese do today. Their pictures, however, are not reduced to a fixed alphabet... with the result that a tremendous strain on the memory is necessary, which is the contrary of what we propose.' (*On The Art of Combination*, 1666)

Leibniz also discovered *binary arithmetic*, which he thought would be used in his new system, and he sensed that there was something philosophically important in its properties. It was the power of binary that led him to say, '*Omnibus ex nihil ducendis sufficit unum*' (One suffices to derive all from nothing).

His most famous prediction, now often quoted at the head of chapters on computer science, was:

> 'What must be achieved is in fact this; that every paralogism be recognized as *an error of calculation*, and that every sophism when expressed in this new kind of notation appear as a solecism or barbarism to be corrected easily by the laws of this philosophical grammar… Once this is done, then when a controversy arises, disputation will no more be needed between two philosophers than between two computers.[4] It will suffice that, pen in hand, they sit down to their abacus and say to one another, "Let us calculate."…' 1686 (XIV)
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> 'Yet I should venture to say that nothing more effective can well be conceived for perfecting the human mind and that if this basis for philosophizing is accepted, there will come a time, and it will be soon, when we shall have as certain knowledge of God and the mind as we now have of figures and numbers and when the invention of machines will be no more difficult than the construction of geometric problems.'

Not only did he develop the theory but he actually invented the Stepped Reckoner which used marbles and gravity to calculate in binary, apparently the world's first automated calculating machine that could perform all four arithmetical operations (the abacus is not automatic).

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[4] 'Computers' here is used in the sense of human computers.

> 'Many applications will be found for this machine for it is unworthy of excellent men to lose hours like slaves in the labour of calculation which would safely be relegated to anyone else if machines were used.'

Leibniz demonstrated his 'Stepped Reckoner' to the Royal Society in 1674 but tragically it was ignored and it sat forgotten in an attic until 1879.[5]

Vaucanson's duck, punched cards, Babbage, Boole, calculating machines...

Vaucanson's duck. Jacques de Vaucanson, inspired by the Newtonian revolution, decided to build a living machine, a giant duck. It could waddle, quack, eat, and defecate and he claimed that his method had 'copied from Nature'. After it was presented to the court of Louis XV, it became internationally famous (Goethe saw it and called it 'most deplorable'). Vaucanson also created the first automated loom using punched cards in 1745. Half a century later the duck was dismantled and it was discovered that it was a con using a simple clockwork mechanism.

'The Turk'. 'The Turk' was a supposed chess automaton with the appearance of a Turk. It was made by von Kempelen and beat many celebrities at chess, including Napoleon. Von Kempelen had, like Vaucanson, conned Europe. Inside the 'automaton' was hidden a dwarf chess master.

The Jacquard Loom and punched cards. In Paris in 1801, Jacquard first demonstrated his programmable loom using punched cards to control the selection of shuttles containing coloured threads and this allowed the programming of patterns into fabrics. This was the first piece of machinery to be controlled by punched cards. Since the loom could follow instructions, the role of the skilled weaver was soon redundant. Lyon's silk weavers famously destroyed the looms but this early attempt to remove the threat of technology by forced relinquishment failed. Within a decade there were thousands of automated looms.

Babbage. During the Napoleonic Wars, Napoleon embarked on a project to create new maps (for property taxes) and a switch to the metric system. Both required new calculations. This required a team of low paid human calculators (some unemployed hairdressers) filling in tables line by line. It took about a decade and by then there was not the money to publish them so they languished in the *Academie des Sciences* until Charles Babbage, visiting Paris, happened to view the manuscript.

Babbage already had experience of astronomical and actuarial tables and decided to build a machine that could replace the human calculators. He proposed a Calculating Engine in 1822 and got government funding in 1824. In 1832 he produced a functioning model of the Difference Engine and published *Economy of Machinery and Manufactures*. The next year he abandoned the Difference Engine and proposed instead the Analytical Engine which would be capable of multiplying or dividing two 50-digit numbers to 100 decimal places in under a minute, and which could be programmed to evaluate polynomial expressions of any degree. It would have a processor that performed arithmetic (the mill), memory to hold numbers (the store) and the ability to alter its function *via* user input using punched cards 'adapted from those used by the card-controlled Jacquard loom' (Dyson). It was a prototype of a digital computer (a machine that applies instructions to digits to produce digits). Babbage produced thousands of pages of instructions in the hope he could get funding but the Government refused.

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[5] The way in which computer scientists discuss Leibniz, the discussions of Gödel and Einstein as they strolled around Princeton discussing the views of Parmenides and Plato regarding knowledge and time, and the way in which Plato's *Forms* crop up in discussion of brain modules programmed by evolution to perform certain tasks, undermine Dawkins' view that 'pre-Darwinian answers' to questions like 'What is man?' are 'worthless' except for historical interest.

> 'Although framed in a dialect of gears, levers, and camshafts, Babbage anticipated the formal languages and timing diagrams that brought mechanical logic into the age of relays, vacuum tubes, transistors, microprocessors, and beyond… The analytical engine linked the seventeenth-century visions of Hobbes and Leibniz to the twentieth century that digital computation has so transformed.' (Dyson, p.39)

Leibniz had thought that 'one could carry out the description of a machine, no matter how complicated, in characters which would be merely the letters of the alphabet, and so provide the mind with a method of knowing the machine and all its parts.' Babbage would write a century and a half later:

> 'By a new system of very simple signs I ultimately succeeded in rendering the most complicated machine capable of explanation almost without the aid of words… I have called this system of signs the Mechanical Notation… It has given us a new demonstrative science, namely, that of proving that any given machine can or cannot exist.'

Babbage's design anticipated Turing's demonstration that a universal computer could perform any mathematical operation. He also anticipated the idea of stored programs and discussed the library of cards for operations that could 'at any future time reproduce the calculations for which it was first arranged.' In 1991, the Science Museum built a version from his diagrams and it worked, vindicating his design.

George Boole (1815-1864). Boole wrote '*An Investigation of the Laws of Thought, on which are founded the mathematical theories of Logic and Probabilities'* (1854). His goal was:

> '… to investigate the fundamental laws of those operations of the mind by which reasoning is performed; to give expression to them in the symbolic language of a Calculus and … to make that method itself the basis of a general method for the application of the mathematical doctrine of Probabilities; and, finally, to collect from these various elements of truth … some probable intimations concerning the nature and constitution of the human mind.'

In *Boolean algebra*, the symbols +,-,x,= represent the logical operations OR, NOT, AND, IDENTITY operating on variables (x,y,z…) restricted to the binary values 0 and 1. This system brought together logic, maths, and binary. The second half of the book dealt with 'fuzzy logic' (which von Neumann would later consider in his paper '*Probabilistic Logics and the Synthesis of Reliable Organisms from Unreliable Components*') and the way in which 'individually indeterminate phenomena could nonetheless be counted on, digitally, to produce logically certain results' (Dyson). Boole also anticipated von Neumann's conclusion that the brain, using imperfect neurons, must use a statistical language to correct errors. Boolean algebra was intimately connected to *propositional logic* and *predicate calculus* (sometimes called 'first-order logic') developed by Frege (cf. a future blog).

Punched card calculating machines. In the late 19th Century, others began to explore similar ideas to Babbage. In the 1880s, Allan Marquand, an art historian living in Princeton, experimented with a mechanical binary logic machine; a study of Marquand's papers suggest he may have designed the very first electrical data processor though how much of it he built is unknown. The logician Charles Peirce noticed this work and wrote a paper (*Logical Machines*, 1887) exploring 'precisely how much of the business of thinking a machine could possibly be made to perform'. The machine should be devoid of original ideas and we would no more want an original machine than 'an American board of college trustees would hire an original professor.'

The punched card industry was developed by Hollerith in the late 19th Century. The requirements of the 1890 US census provided an opportunity since human counting threatened to take longer than a decade. Hollerith's punched card system recorded 62 million people using 56 million cards in much more detail than had been possible. Hollerith incorporated the Tabulating Machine Company in 1896 which morphed into IBM in 1924. A 1922 *Scientific American* article discussed how the development of punched cards 'can endow inanimate machines with brains of their own'. Dyson writes that, 'By the time Turing awakened us to their powers, the age of discrete-state machines was well under way.'

Optical data networks.

'Two distinct functions are required of a successful telegraphic code: the encoding of protocols that regulate the process of communication, and the encoding of symbols representing the message to be conveyed. Meaning … is encoded hierarchically: first by mapping elementary symbols to some kind of alphabet, then by mapping this alphabet to words, phrases, standard messages, and anything else that can be expressed by brief sequences of code. Higher levels of meaning arise as further layers of interpretation evolve. Protocols … initiate the beginning and end of a transmission and may be used to coordinate error correction and flow control.' (Dyson)

Optical data networks have a long history. For example, Clytemnestra ordered a network of beacons to bring news of the fall of Tory to her 375 miles away in Mycenae. At the beginning of Aeschylus' *Agamemnon*, the chorus asks, 'And what messenger is there that could arrive with such speed as this?' and Clytemnestra answers, 'Hephaistos, sending forth from Ida a bright radiance. And beacon ever sent beacon hither by means of the courier fire … so as to skim the back of the sea … transmitting, like a sun, its golden radiance to the look-out…' It was what would now be described as a 'one-way, one-time, and one-bit channel encoded as follows: no signal meant Troy belonged to the Trojans; a visible signal meant Troy belonged to the Greeks. Communications engineers have been improving the bandwidth ever since' (Dyson).

Polybius a thousand years later told how the Romans had improved the idea. When the Spanish Armada set sail in 1588, beacons spread the news. The telescope extended the distance between relay stations in the 17th Century. Robert Hooke wrote '*On shewing a way how to communicate one's mind at great distances*' using optical signals and a coding system that would allow signals to be exchanged securely between London and Paris in a few minutes. After scorning Leibniz's computer, put on show in 1673, Hooke built his own a few months later 'whereby in large numbers, for multiplication or division, one man may be able to do more than twenty by the common way of working arithmetic'. Unfortunately, though listed among the rarities in the collection of Gresham College in 1681, it then vanished. Hooke estimated the storage capacity of the brain by calculating the number of thoughts per second and estimated a figure of about 2 billion of which he thought about 100 million could be remembered.

In 1790, Claude Chappe tried to build an electric telegraph but abandoned it in favour of optical signals relayed by mechanical display. His prototype was destroyed twice by mobs thinking it was a scheme to signal to Louis XVI. In 1794, he built a link between Paris and Lille. In 1801, Napoleon tested a system in France for imminent use across the Channel after his invasion of England. By 1800, 'optical telegraph networks spanned most of Europe'. By 1852, the network had a total length of 3,000 miles with 3,000 operators in 556 stations about 6 miles apart. Signals could be relayed in a few seconds though in practice it ran slower. Sending a signal from Paris to Toulon took about 10 minutes. It was imitated across Europe, with the link between London and Plymouth conveying a message in three minutes.

Electric telegraph. In 1729, Stephen Gray transmitted an electric charge 765 feet. In 1747, after the invention of the Leyden jar, Watson transmitted an electric charge across the Thames. In the second half of the 18th century, there were many experiments and business ventures with electric telegraphy. In 1800, Volta announced the first electrochemical battery. In 1819, Oersted outlined the principles of electromagnetism and in 1820 Ampère gave the subject some mathematical precision. He also discussed connecting a keyboard to an electric telegraph. In 1816, Francis Ronalds transmitted electrostatic signals over eight miles of wire and then tested his apparatus with 525 feet of insulated wire buried in underground cables. Ronalds tried to get the Navy interested but was told that 'telegraphs of any kind are now wholly unnecessary'. Many different schemes were tried and failed. In 1833, the great mathematician Gauss and Weber constructed a 1.5 mile system to share information using binary signals between the Göttingen physics department and observatory. In the1830s, various telegraph systems were deployed in Europe and America.

After a trip to Europe in 1832, Morse developed his language and the first long-distance line opened in May 1844 between Washington and Baltimore. The electric telegraph industry soon took off. In 1851, the first cable linked England and France, by 1852 there were 23,000 miles of telegraph lines, in 1861 the first line spanned North America, in 1866 the first line connected England and America, and in 1870 India was connected to Europe.

> 'Telegraph signals were digital signals, whether conveyed by the on-off state of a fire beacon, the twenty-four symbol alphabet of Robert Hooke, the ninety-eight-state signal of the Chappes, a series of positive-negative voltages, or the dot-dash sequences of Morse code. To process these signals requires discrete-state machines, whether the machine is a human operator looking through a telescope and referring to page and line numbers in a book of code or one of the punched tape teleprinters that soon came to dominate telegraphy… *Telegraph engineers were the first to give substance to what had been shown by Leibniz … and would be formalized by Alan Turing …: all symbols, all information, all meaning, and all intelligence that can be described in words or numbers can be encoded (and thus transmitted) as binary sequences of finite length*. [Emphasis added.] It makes no difference what form the symbols take; it is the number of choices between alternatives that counts. It takes five binary alternatives ($2^5 = 32$) to encode the alphabet, which is why early needle telegraphs used five separate two-state indicators and why teletypewriter tape is five holes wide. Polybius had specified two separate five-state indicators, a less efficient coding that makes sense if you are keeping a naked eye out for torches in the dark.' Dyson

The telegraph system evolved 'store-and-forward' procedures. An incoming signal to a switching node arrived as electric signal, was converted to punched paper tape identified by origin, address etc, then, after decisions by the station operators, was retranslated back to electric signal by machines that recognised the tape patterns, and sent on along the network. This was 'the ancestor of the packet-switching protocols used in computer networks today'.

> 'It was only natural that the first computers incorporated high-speed telegraphic equipment, and it is no accident that the genesis of the Colossus … was mirrored … by early steps taken toward computers by Claude Shannon... [As computer-computer communication rapidly evolved from the 1940s] no matter what the medium of exchange, the code itself and the protocols that regulate its flow remain directly descended from the first strings of telegraphic bits.' Dyson

Wireless communication. Tesla mastered wireless communication in 1893 and five years later he demonstrated the use of radio signals to control a motorboat in Madison Square Garden. Afterwards he asked the Government if they wished to buy his invention and the civil servant 'burst out laughing upon telling him what I had accomplished.' In 1917, the 'land torpedo' was built to drive explosives to enemy positions and detonate. The Kettering 'Bug', or aerial torpedo, was a small remote controlled unmanned plane using a preset gyroscope and barometer to fly to, and crash into, a target fifty miles away. They remained essentially prototypes and did not influence the outcome of the war. Germany used special motorboats (FL-7s) designed to be rammed into British ships by electronic control to protect their coast. In 1916, they switched to radio waves (from cables) and this may have been the first application of Tesla's discovery to warfare (Singer).[6]

At the end of World War I, Scherbius proposed a machine that would scramble a message in one place (using a computable function) and unscramble it at the other end (by someone who knows the function) to deliver secure communications. He offered his idea to the German Navy who rejected it so he formed a company to build it himself. The 'Enigma' coding system was born and was adopted by the German Navy from 1926. (Dyson, Ch.4)

The analog 'Differential Analyser'. Until World War II, computing devices were only analog. In order to predict, say, an eclipse observatories hired teams of people ('calculators') to do the calculations by hand. One could also create an analog computer (a mechanical analog of the system) that would model the solar system with gears and shafts and run the time forward (the planetarium is also an analog computer). Before World War II the Differential Analyzer, developed by Vannevar Bush at MIT in 1929, was the leading analog computer and could approximately solve differential equations without numerical processing. 'Programming' involved setting the machine into a start state with screwdrivers, spanners and hammers.

> 'In the Differential Analyzer, motors powered shafts that turned wheels that corresponded to variables in the continuous (differential) equations defining a problem such as aiming an antiaircraft gun or operating a power grid. By selecting where the wheels rolled against other wheels, and how the shafts connected among them, the relative rates of the rotations would add up to a solution to the problem… It weighed in at a hundred tons. Programming it was an oily process, requiring days to set the ratios of the wheels and the connections of the motorized shafts… Even when everything did work, every step in [its] operation added an error of about a tenth of a percent.' (Gershenfeld)

There were about a dozen copies one of which was at the US Army's Aberdeen Proving Ground in Maryland which prepared weapons for deployment. Soldiers had to look up the angles for elevation in books of tables. Each table entry required the integration of many differential equations. A human would take days; the Differential Analyzer took about 20 minutes. In 1936, Bush predicted a shift to digital machines. The same year, Turing's famous paper was published - '*On computable numbers, with an application to the Entscheidungsproblem*' - and modern computers were soon born.

In a future sketch in this series, I will explore the discussions concerning Gödel and Turing which simultaneously transformed 1) the foundations of mathematics and logic, 2) the field of computing, and 3) ideas concerning the possibility of machine intelligence and automated reasoning. Separately, I will also sketch some of the developments in computing during World War II. Discussions concerning these issues 1931-45 also became entangled with general discussions about complex systems in economics, 'information theory', and the brain. Von Neumann was involved in all of these fields and helped coordinate many of the different players (cf. previous blog).

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[6] In World War II, Germany fielded the first cruise missile (V1), the first ballistic missile (V2), the first jet fighter (Me-262), and the first unmanned drones - the FX-1400, a 2,300 pound bomb with four wings that would drop out of a plane and be guided to its target. (A similar American project was Operation Aphrodite, a prototype of which blew up killing Joe Kennedy's eldest son, JFK's elder brother. The Army cancelled the drone programme and JFK changed career.) The first mass produced unmanned plane was the 'Dennymite', named after a British actor who hit the big time in Hollywood and started a company after seeing a radio-controlled airplane on a movie set (Marilyn Monroe was spotted working in his factory). America's Norden bombsight was a great advance. It was an analog computer that was installed in a plane and could calculate the trajectory of bombs and drop them automatically. It was almost as expensive as the Manhattan Project and the individual sights were so valuable that they were stored in safes between missions. Norden was so cross with the US Army Air Corps that he sold it to the Navy for $1. A Norden sight was used to drop the nuclear weapons on Japan. Cf. Singer, *Wired for War*.