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ESSAYS IN COMPUTATIONAL MANAGEMENT SCIENCE

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Part I

INTRODUCTION

1 INTRODUCTION

It is still an unending source of surprise for me to see how a few scribbles on a blackboard or on a sheet of paper could change the course of human affairs.

— Stanislaw Ulam

If anything good can ever be said about the second world war, it might be this: the war effort sparked a massive number of scientific fields.

Though most fields existed prior to the war, after the war they were funded by the public as strategic pieces of the major nations arsenal against future conflagrations. One of the fields in question was that of Management Science (also called Operations Research in military circles, as researchers filled the ranks of planners of war operations). Management Science had started as an industrial field, in movements stemming from Taylor and the origin of the production line by Henry Ford. That was the first moment in industry in which operations were systematically subject to some of the tools of science: measurement, experimentation, hypothesis-testing, statistics, mathematical optimization, etc.

This humble beginnings date from almost 100 years ago. Today the field has advanced to a great number of nations, and the amount of applications has grown explosively. Of particular interest to us is the advent of the computer, and of engineering efforts that brought exponential growth in computational power to the hands of individuals. Whilst, during the war, computations were mostly done by hand, the electronic computer took over afterward; up to an extent that it is not outlandish to say that this original field can be referred to, today, as *computational management science*.

Applied mathematics and computer science serve simultaneously as a theoretical foundation and the major tool available to the field. Though this is a doctoral thesis concerning business, in this document one should expect to find the language and nomenclature of mathematical modeling and computer science as our primary and most natural language.

This thesis will explore three different topics related to *computing business platforms* (Figure 1). Though the range of the topics is large, as it usually is in management science, it is my hope to convince readers of the value of this doctoral thesis brought by three specific, self-contained, scientific papers — the first of which studies the possibility of distributed financial ledgers.

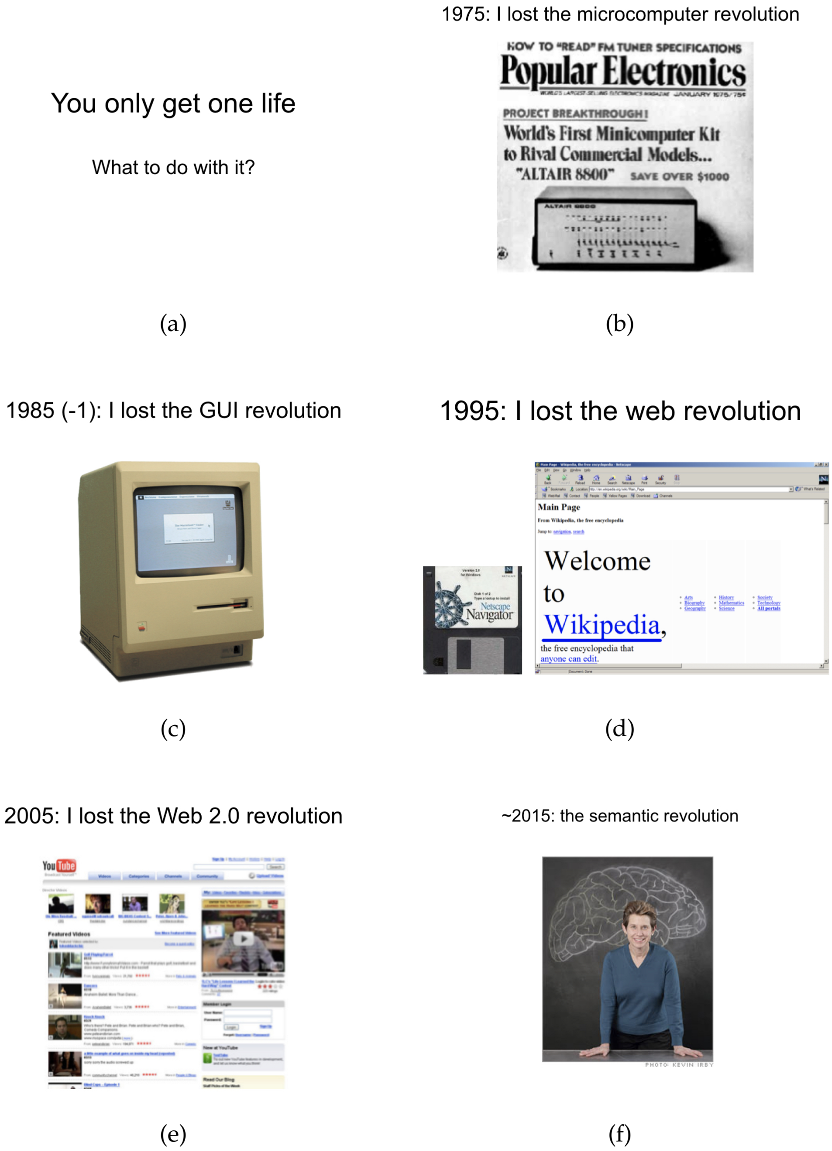

Figure 1: Slides from an old Linhares' class; a viewpoint that has influenced the choice of topics found in this thesis. In the history of computing business, the most interesting level of analysis seems to be that of the *platform*. It is where things can get built on top of, and communities emerge, and standards fight against each other, and fortunes are built or lost. It is, in a sense, a major part of the Big Drama of our moment in history. Each time a new computing platform appears, it seems as the opportunities are ripe for the taking; as if a multitude of doors have opened simultaneously. Note that the slides were made in 2007, and expected an AI-based 'semantic revolution' by 2015 [10]. In between, both the iPhone (and competitors) and Bitcoin (and competitors) have created giant platforms on top of which immense wealth has been created (Uber, Instagram, etc, on the case of smartphones; and exchanges, miners, investors, payment processors, etc., in the case of blockchains). The key point is that we should (i) expect new, unforeseen, technological platforms, (ii) rapidly identify them, and (iii) throw our energy at them, as they offer leverage to make an asymmetric impact.

1.1 DISTRIBUTED FINANCIAL LEDGERS

The World Bank estimates that there are two billion people without access to financial services. As banks are unable to sustain operations in numerous poverty-stricken areas, services such as money transfers, access to credit, digital/distant payments, inflation protection, etc., remain beyond reach for 'the unbanked'. This seems to be one of the factors that perpetuate poverty. The Bill and Melinda Gates Foundation chose as focus of its "Level-One project": to provide basic financial services through cell phones. Another initiative, the United Nations World Food Programme has begun, in 2017, an experiment in Jordan, in which the organization provides funds for thousands of people towards its goal of food relief. An interesting aspect of this program has been the format of the funds distributed: they have been all on the ethereum blockchain [16, 14, 15].

The possibility of having a completely digital financial system without the overheads of traditional banking systems has appeared with the release of Bitcoin and similar blockchain technologies. This field questions numerous traditional assumptions in computer science, record-keeping, banking & finance, and economic inclusion. The seminal work of Nakamoto [11] described the architecture of Bitcoin, a peer-to-peer electronic cash system, also known as cryptocurrency. Bitcoin's currency ledger is public and stored in a blockchain across thousands of computers. Even so, no one is able to spend either somebody else's funds nor to double spend their own funds. In order to be confirmed, each transaction must be both digitally signed by the owner of the money and the funds verified in the blockchain by Bitcoin's miners. The question of whether Bitcoin (or related works) can scale to billions of people is, however, far from settled.

One of the interesting parts of Bitcoin are the incentives. On one hand, users have incentive to use Bitcoin because the fees are small, the money transfer is quick and global, and the currency issuance rate is well known. On the other hand, the miners have incentive to be part of Bitcoin's network because, every ten minutes, new coins are found and transactions' fees are collected. These incentives keep the community together and have maintained Bitcoin alive.

The impact of Bitcoin in society — and hence in the companies and the government — has been growing every day. People are increasingly using Bitcoin to exchange money and transfer money overseas. Companies are looking into Bitcoin as an alternative to reduce banking fees. The poor may be included in the finance system through Bitcoin. People may hedge their assets against their governments' money issuance and inflation — as in the case of Venezuela.

Bitcoin is the first and most famous cryptocurrency, used worldwide, with a highly volatile market cap, as of this writing, of $ 192 bi. Even so, it faces serious scalability challenges; such as serious quality of service and network congestion when the number of transactions per second is high, and an increase in the transaction fees and uncertain delays in transactions' confirmations.

Note that these problems have been a deliberate decision from the current developers of the "bitcoin-core", which believe that is it risky to increase the blocksize (in which all transactions are stored). It is not known whether a blocksize, say, of 1GB, would be feasible to sustain the decentralization of the network.

Iota is a second cryptocurrency that, instead of using a blockchain, proposes the use of a "tangle' architecture': a different way to register the currency ledger across thousands of computers. Although it has not been confirmed in practice yet, its architecture seems to be significantly more scalable than Bitcoin's blockchain. As we will see, the problem here is exactly the opposite of Bitcoin's. Iota needs a minimum of transactions per seconds in order to work properly.

Our analysis suggests an architecture for a distributed currency which is inspired in both Bitcoin's blockchain and Iota's tangle in order to solve the scalability problems. While Bitcoin's network saturates when it hits a certain number of transactions per second, Iota's does not work properly with less than a certain number of transactions per second. Our proposed architecture seems to work in both scenarios: low and high number of transactions per second.

In this first study we will investigate some issues regarding this possibility, namely: (i) cryptographic security and game-theoretical attacks; (ii) scalability; (iii) self-governance of the system; (iv) appropriate incentive system to all participants.

A second topic that may have an outsized influence on business and that we will be taking a closer look is a model of artificial intelligence — and of human decision making.

1.2 SPARSE DISTRIBUTED MEMORY

A significant part of the thesis is devoted to *Sparse Distributed Memory*, or SDM for short. There are two reasons for that: first, it is an important topic in artificial intelligence and computational cognitive science — a crucial piece of technology that may eventually have vast influence throughout society.

But it is perhaps more than that. Perhaps it is a crucial item in understanding human decision making. SDM may, perhaps, bring us a formal model of *recognition-primed decision*, put forth by Gary Klein as a theory of decision-making.

1.2.1 *Decisions with serious skin in the game*

The recent field of *naturalistic decision making* stands as a new alternative model of study of decision-making. It bears contrast to both the classical model of rational choice and to the program of heuristics and biases.

The classical model of *rational choice* and optimization which has been the basis of studies in economics (for instance, in game theory), management science and operations research (in for example mathematical programming models), and in artificial intelligence (the symbols and search paradigm), proposes a set of standard, quantitative, methods in order to 'rationally' select a choice. Under this theory, the decision-maker:

1. identifies a set of options,
2. identifies ways of evaluating these options,
3. weighs each evaluation dimension,
4. calculates a rating of each option, and, finally,
5. selects the one with the maximum score.

Note that this model implies that, in order to have a number of choices to choose from, one must first have (i) perceived a problem, and (ii) perceived a set of alternative choices — where do the choices come from? What psychological process brings forth their emergence? The rational model will deal only with the phase of (iii) selecting one choice from the set.

Despite its widespread use in a number of distinct areas, the rational choice model has not found to be psychologically plausible, for a number of reasons [13]. One of the reasons is that the chosen alternative depends on how decision-makers initially frame a problem (Kahneman and Tversky, 1979). There has been strong criticism of the rational choice model from the heuristics and biases research program, in which problems are carefully devised to show that one's intuitions generally depart from the expected optima, and are generally inconsistent with what would be expected as rational. A large number of biases that depart from rational choice have been found (see, for instance, Plous [13]), placing strain on the traditional rational actor doctrine. Yet the heuristics and biases studies are concentrated on carefully devised questionnaires applied mostly to undergraduate students — not on real world settings with serious skin in the game.

Thus a new field of naturalistic decision-making emerged, in which the focus is centered around real life settings and decisions being made under rapidly changing circumstances. A number of studies have been conducted, from firefighters to nurses to chess players to military personnel. One of the most interesting theories to emerge from naturalistic decision-making, the recognition-primed decision model, was devised by Gary Klein and his colleagues (Klein, 1999).

1.2.1.1 *Recognition-primed decision*

Consider the following cases:

EXAMPLE #1. The Cuban World Chess Champion José Raoul Capablanca once remarked about his personal, subjective, experience: 'I know at sight what a position contains. What could happen? What is going to happen? You figure it out, I know it!' In another occasion, talking about the numerous possibilities that less-skilled players usually consider on each board position, he bluntly remarked: 'I see only one move: The best one.' Perhaps the reader may think that Capablanca was quite simply being arrogant. But there is evidence to the contrary, that expert decision-makers actually are biased towards very high quality choices. We believe that, in fact, Capablanca was telling us an important fact about expert human psychology and decision-making, which would later be documented in recognition-primed decision studies.

EXAMPLE #2. A baby at an infirmary suddenly turns blue. Within seconds, a nurse has a diagnosis and a potential action. In this case, the nurse thinks the baby has a pneumopericardium, which means the sac surrounding the baby's heart is inflated with air, and the resulting pressure detracts from the heart's pumping of blood. There is a problem with this diagnosis, though. The electrocardiogram is showing a healthy 80 beats per minute. If nothing is done, the baby will die within a few minutes. The doctor walks into the room to find the nurse screaming for silence and listening to the baby's heart with an stethoscope. She is now sure of her diagnosis, and she gives the doctor a syringe: "stick the heart, it's a pneumopericardium, I know it". Given the electrocardiogram, other nurses are skeptical, until the x-ray operator screams out: "she's right!" Her intuitive diagnosis ultimately saves the baby's life.

Klein (1999) conducted a series of studies with decision-makers under rapidly changing scenarios. During interviews, when questioned how a specific decision (or course of action) was adopted, decision-makers such as the nurse would proclaim, to Klein's frustration, that they 'did not make decisions'. One experienced firefighter proclaimed 'I don't make decisions–I don't remember when I've ever made a decision' (Klein, 1999, p.10). Decision-makers did not seem to be comparing alternative courses of actions, as classical models would predict. 'It is usually obvious what to do in any given situation' (p.11). Repeated statements of the sort by different decision-makers led Klein to propose a psychologically plausible model of decision-making which radically departed from the established view of 'comparing alternatives and selecting the optimum'.

Klein (1999) proposed a model of recognition-primed decision, in which experienced decision-makers would find themselves immersed in complex situations and rapidly take adequate courses of action. Decision-makers would rapidly perceive cues from any situation and retrieve from episodic memory similar situations (Tulving 1983), which would bring assessments and diagnoses and plausible courses of action. Because priming mechanisms are automatic and unconscious (Bargh and Chartrand 1999, Bargh et al. 2001), these decision-makers reported doing 'the obvious' action in different situations. This 'obvious' course of action, Klein proposes, is brought from long-term episodic memory by priming mechanisms. Hence, decision-makers would not be selecting among distinct alternatives, but rather simply performing the automatically-provided action.

Even if the 'obvious' action seemed plausible for a theory, another problem remained: if decision-makers did not compare alternatives, then how could they know that a course of action was good? In subsequent interviews, evidence emerged that decision-makers would be using the simulation heuristic, proposed by Kahneman and Tversky (1982). That is, facing a particular situation, experienced decision-makers would be primed towards a particular course of action, to the detriment of most alternative courses of action. This primed alternative would be 'simulated', or 'run through', one's mind, and, if found acceptable during the simulation processing, would be acted upon without further deliberation. If problems emerged during mental simulation, another different course of action would be primed. Thus was born a theory of intuitive decision-making, in which experienced people would not be selecting choices from a vast set of alternatives, but instead 'testing' their initially primed predispositions with a simulation heuristic.

This model, of course, applied only to expert decision-makers with years of experience. It involves access to a large episodic memory in order to rapidly retrieve a suitable course of action. This was initially found surprising by Klein:

> Before we did this study, we believed the novices impulsively jumped at the first option they could think of, whereas experts carefully deliberated about the merits of different courses of action. Now it seemed that it was the experts who could generate a single course of action, while novices needed to compare different approaches. — Klein (1999, p.21)

Because priming mechanisms that brought plausible actions to mind are unconscious, people would report having "done the obvious thing to do". Decision-makers would be unable to visualize the cognitive processes underlying their decisions, and would in many cases even believe that they had skills of the 'fantastic' variety: One firefighter demands that his whole crew abandon operations inside a house, just to see it collapse seconds afterward. A radar operator would 'chill' after spotting a new track, and would fire counter missiles against it, based on the 'feeling' that it was a hostile missile. It took over a year for this radar operator, after being interviewed by Klein, to understand the incredibly subtle cues that he was responding to whenever he perceived the new radar track. Unable to reasonably explain their life-saving, rapid, decisions, both the firefighter and the radar operator thought that they had ESP or other fantastic abilities. Careful probing would show that they were able to unconsciously perceive subtle cues, which primed them towards adequate responses.

Beyond a formalization of this process of memory recall, Sparse Distributed Memory will offer us a plausible, both psychologically and neuroscientifically, path towards artificial intelligence.

1.2.2 *Artificial Intelligence*

Technology has been one of the underlying engines behind economic growth. It has been changing the whole society – people, companies, and governments. Cities and houses had to be rethought when cars became popular. Trains allowed distant places to exchange high volume of goods. Airplanes and boats opened countries to overseas business. And, finally, the internet has had a profound impact in nearly everyone's life, as it changed everything – from the way we communicate, behave, do business, do shopping, share ideas, and so forth.

One area of technology that has been redefining business is computer science. Together with the internet, computer science has been one of the most important tools to scale a business model – and create many others which were impossible before. More and more expensive human labor has been replaced by algorithms. Managers are able to make better decisions because they receive real-time information. The supply chain has incredibly evolved thanks to advances in logistics supported by routing algorithms, storage algorithms, and many others optimization algorithms.

Artificial intelligence has been disrupting many businesses. Uber is able to handle hundreds of thousands of requests. Amazon optimizes the location of each product based on demand. Netflix increases the quality of their services offering movies specific to the taste of each customer. Spotify learns which kind of music users like the most and suggests playlists. Banks prevent fraud classifying which patterns seem to be erratic towards their customers' previous behavior.

It is gradually becoming impossible to imagine a world without artificial intelligence.

Behind artificial intelligence systems, there is pattern recognition: The capacity to match information from new data with information which has already been seen and is stored in memory. It may be used in classification, face recognition, character recognition, and so forth. Even if AI cannot yet solve numerous hard problems — such as the Turing Test, Bongard Problems or simply understanding when 'Lawyers are sharks' [6, 7, 9, 8] —, it is clear that the technology must be taken seriously.

The second paper lies at the intersection of cognitive psychology, computer science, neuroscience, and artificial intelligence. Sparse Distributed Memory, or SDM for short, is a theoretical mathematical construct that seems to reflect a number of neuroscientific and psychologically plausible characteristics of a human memory. SDM has already been used to different pattern recognition problems, like noise reduction, handwriting recognition, robot automation, and so forth.

We implement a BW-Complete[1] SDM framework that not only shows small discrepancies from previous theoretical expectations, but also may be of use to other researchers interested in testing their own hypotheses and theories of SDM. The computer code has been used in a previous Ph.D. Thesis; the code has shown some small discrepancies from theoretical expectations; the code has been run on a number of different architectures and information-processing devices (e.g., CPUs, GPUs). The framework enables us to have a visual exploration previous experiments and new possibilities for SDM.

1.3 DIFFUSION OF INNOVATION

In 2014, a group of Princeton's researchers predicted that Facebook's users would abandon the platform by 2017 [5]. The forecast was done applying a disease spreading model which has correctly predicted the abandonment of "MySpace". Facebook replied after applying Princeton's methodology:

> "Using the same robust methodology featured in [Princeton's] paper, we attempted to find out more about this 'Princeton University' — and you won't believe what we found!". Then, they conclude: "This trend suggests that Princeton will have only half its current enrollment

1 'BuzzWord-Complete: the model is (i) Open-Source, (ii) Cross-Platform; (iii) highly parallel; (iv) able to execute on CPUs and/or GPUs; (v) it can be run on the 'cloud'; etc.

> by 2018, and by 2021 it will have no students at all, agreeing with the previous graph of scholarly scholarliness. Based on our robust scientific analysis, future generations will only be able to imagine this now-rubble institution that once walked this earth".

Whilst this brouhaha reminds one of the dangers of extrapolation, our third paper will revisit the prospects of our esteemed colleagues in Facebook. Lying at the intersection of Marketing, Diffusion of Technological Innovation, and modeling, the Bass model of diffusion of innovation will be extended, in order to account for users who, after adopting the innovation for a while, decide to reject it later on (possibly bringing down the number of active users—something impossible in Bass' original model). Four alternative mathematical models are presented and discussed with the Facebook's users dataset.

1.4 THE FINE PRINT...

Before embarking on the technical topics, small qualifications must be asked from my readers. First, as stated above, though these problems have immense and urgent importance to the fields of study in business, the language in which we will approach them and discuss them most naturally will be that of mathematics and computer science. There will not be surveys, interviews, questionnaires, or such methods typically used in the social sciences: This is basically a work of modeling.

A second and final qualification: It is my hope that readers of this thesis will accept the format of self-contained studies, as just as valid as a monograph on a particular topic. With these qualifications, we are ready to venture into the world of computational management science.

Part II

CONCLUSION

2 CONCLUSION

Software is eating the World.

— Mark Andreesen [2]

Modern management and high technology interact in multiple, profound, ways. Software — given the widespread availability of general-purpose Turing-complete hardware — seems to have an immense power of entering arenas which seemed, at some point, to require either specific hardware or the skill of humans. One of the members of this thesis committee, Dr. Nichols, will participate through teleconferencing over the open web, with no use of hardware specific for the task. The corporate biography of Tonny Martins, President of IBM Brasil, mentions his successes with blockchain, AI, and cognitive technology. . . as an executive, not as a research scientist or specialized engineer [3]. Professor Andrew Ng tells students at Stanford's Graduate School of Business that "AI is the new electricity" [12], as his hyperbolic way to emphasize the potential transformational power of the technology.

It is not impossible that a purely digital form of money may exist. It is not impossible that machines may become intelligent. Moreover, it is not impossible that these two processes may have already begun.

It is worthwhile, in this concluding section, to reflect on some ideas on what this thesis is and what it is that we, as computational management scientists, can obtain from this sort of study. Clemenceau once said that "war is too important to be left to the generals". I believe it is not far-fetched to state that technology has become too important to be isolated to the realm of computer science, or engineering, or applied mathematics, or any single discipline. The emergence of scientific journals with names such as Computational Management Science; INFORMS Journal on Computing; Ledger; Computational Statistics; ACM Transactions on Economics and Computation, and so forth, show that there are growing communities deeply interested in the intersection of business and the computer sciences. To whom, for instance, does the OpenAI project belong? To computing or to business? Recall that the project was created as a risk-management strategy against the far-fetched, science-fiction sounding — but not impossible —, possibility of having machines yielding too much power. What about corporations like Uber? AirBnB? Imagine a new method that increases profits by 50% at a tech company. Should this method, if implementable as an algorithm (like PageRank [4]) or a data structure (like a blockchain) be discussed in conferences of 'computer science' or 'business'? It seems quite arbitrary to name a single group, as a whole new ecosystem seems to have emerged within those two. That is why this thesis is computational and why it is business. This work explores topics that seem, on the surface, to belong to computer science, but their applicability and impact to businesses seem too large, too central, to be delegated away, something "for those nerds in the fifth floor". As technical decisions become central to the organization of man's life, the technician becomes the visionary, the innovator, the decision-making arbiter, sometimes the billionaire.

The possibility that there will be some form of purely digital money has become very real; and we have started this study with two possible forms of organization of a purely digital money system; a blockchain and a directed acyclic graph. Consider, just as a matter of comparison, Brazil's most important company: Petrobras. As of this writing, the "market cap" of Ethereum exceeds that of Petrobras by ten billion dollars, while Bitcoin's is valued at more than double of Petrobras (195B usd vs 83B usd). Prices change, of course; but these technologies should, at a minimum, be taken seriously.

We have explored Kanerva's Sparse Distributed Memory. In AI, SDM seems to be a particularly interesting area for study. The model plausibly reflects a number of well-known aspects of psychology and neuroscience. For example, neurons can easily compute the address decoding scheme of the system. Neurons are fragile and may be lost, whereas the information remains preserved, due to the distributed character of the model. The "tip-of-the-tongue" behavior emerges naturally, and so does Miller's magic number.

There are at least three contributions[1] made on SDM: First, I have illuminated a discrepancy between Kanerva's theoretical model and the real system dynamics; Also, we have seen that pattern classification through supervised learning is possible without presuming any new SDM mechanism. This is in contrast with the literature, that presumes additional mechanisms, like genetic algorithms, to account for supervised learning. Finally, we now have a tested open-source framework that offers parallelism and can become a de-facto standard in SDM research. The framework (i) carefully reproduces crucial figures from Kanerva's theoretical book; (ii) shows how noise filtering and (iii) supervised learning can be done, and, through the use of (iv) Jupyter Notebooks, enables the reader to easily reproduce all the results on their own machines. This respects all constraints posed by Robert M. French in his article

1 As many issues have been explored in less detail, it might be advisable to leave it to history to decide whether these explorations were actually contributions.

on ‘Computational Modeling in Cognitive Science: A Manifesto for Change’ [1].

The ability to rapidly reproduce results, and to build on prior work, is, I believe, fundamental to modern science. Consider, for instance, the groundbreaking successes in the arena of deep learning. Having standard computer libraries to work with has brought together a community, which reinforces the system, as users also gradually improve these libraries. It may be possible to achieve new results with multiple layers of a SDM, yet, having to start development from scratch takes a large opportunity cost from most scientists — especially those who are less concentrated on the computer science aspects, but still would be able to contribute meaningfully.

Finally, we have studied how variations of the Bass Model may reflect systems or technologies that may wither in time. Though some innovations, such as the radio, have gained widespread use in a sustainable form... One may want to review the Bass model when one is concerned with rapidly-evolving technological ecosystems. Hardly anyone remembers the names AskJeeves, World Wide Web Worm, Lycos, WebCrawler, or AltaVista, early web search engines; later replaced, in the market and by the market, by the almost unnoticed url `http://google.stanford.edu` [4].

Another possibility would be to compare the proposed model with a computation of the momentum of Metcalfe’s law in between competitors. As the reader may remember, Metcalfe’s law states that the value of a network grows $O(n^2)$ with n being the number of network nodes. If the proposed model and Metcalfe’s network effects reflect reality, then there could be an integrated mathematical model that explains and represents both Metcalfe’s law and the variation of the Bass model presented herein.

With this, I submit this thesis in the hope that all readers, present and future, may find the aforementioned studies as useful, genuine, and legitimate contributions to the thriving field of Computational Management Science[2].

2 Finally, for the skeptical reader that may argue against the decision towards ‘arbitrary technical reports on unrelated topics’, a reference to the “fundamental research theorem”, reprinted in Appendix **??**, seems, of course, virtually inescapable.

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