

Bourbaki vs Pragmatism

A methodological comparison through the multi-armed bandits problem

DRAFT

Sebastiano Ferraris*

June 6, 2021

In these pages, through the example of the the multi-armed bandit problem, you will find a comparison between two methodological approaches to mathematics. The two methods are here named the *Bourbachist* and *pragmatic*: the Bourbachist way is concerned with the mathematical foundation upon which a formal solution emerges from a set-theoretical axiomatic structure. The other way, the pragmatic one, is focused on the algorithmic solution, and the underpinning mathematical formalisation appears only when needed. In this article you can also find a brief literature review about the history and origin of Bourbachism, and a shortlist of other notable examples where the same problem has been addressed in the bourbachists and in the pragmatic way. The article concludes with a final discussion about the advantages and disadvantages of each approach, after exploring the reasons why the Bourbachist formalisation is still so widespread.

If you discovered this article while searching for an introduction to the multi-armed bandit problem, please look directly at section 3. The code to create the figures, to run and compare a range of solutions to the multi-armed bandit problem is versioned controlled and open to contributions at the link <https://github.com/SebastianoF/multi-armed-bandits-testbed>.

1 Two ways to approach the multi-armed bandits problem

Imagine you have to repeatedly choose between K different options. All options have the same cost, though each may or may not provide you with a reward. The probability

*sebastiano.ferraris@gmail.com

1 Two ways to approach the multi-armed bandits problem

of having a reward is modelled by an *unknown* distribution, that may be different for every option and that can vary over time.

This general setting is of concern for a wide range of problems, such as choosing a medical treatment or a drug, randomising quality control of produced parts, exploring new cafes, trying a range of cars before buying one, choosing a job, and for the most daring ones, selecting a partner. In the algorithmic literature the setting is referred to as the *multi-armed bandits* (MAB), as it can be seen as the situation of playing repeatedly at a row of K slot machines, and after the nickname *armed bandit* for slot machines.

The reason why the algorithm takes its name from the gambling example and not from one of the others, more interesting and available in literature¹ is that the gambling case is the easiest to generalise and the one where the algorithmic machinery employed is also easier to visualise. So, following the tradition, imagine to be on a trip to Las Vegas with an initial amount of money to invest in a row of 10 slot machines. Let's say you start with \$1000, and that each draw costs \$1, this gives you 1000 attempts to play and to balance an *exploration* phase with an *exploitation* phase. In the exploration phase the goal is to find an estimate for the unknown distributions of each arm. The exploitation phase aims at using the acquired knowledge to gain the highest possible reward in the face of uncertainty².

The goal here is to provide a solution to the MAB problem, following two different mathematical approaches:

- *Bourbachist approach*. Named after the collective pseudonym of the group of French mathematicians who have developed this viewpoint in 1934, it is driven by the need of providing a strict formalisation of the theory from a set theoretical perspective, whose conclusions are a consequence of a list of axioms, and where the physical intuition is completely excluded.³
- *Pragmatic approach*. In contrast to the Bourbachist approach, the pragmatic one reduces the formalisation to its bare minimum, and it orientates your efforts into finding a solution of a problem usable in practice, rather than creating a formal axiomatic theory.

¹For example Bouneffouf [BR19].

²Thompson [Tho33] provides an early exposition to the method where the two arms are two medical treatments, Bellman [Bel56] formulates the problem in a Bayesian perspective, again for two arms, and the more recent Sutton [SB18], Chapter 1, consider the problem as a starting point to introduce the field of reinforcement learning.

³Historically, the Bourbaki group had the initial goal of re-writing one of the most widely used analysis textbook of the time, the Goursat's *Cours d'analyse mathématique*. The reason for this endeavour was that the group had considered the book inadequate, since few counterexamples contradicting some of the claims were found (Marmier [Mar14]). To this end the group decided to turn mathematics into the manipulation of axiomatic systems independent from physics, rewriting the whole corpus of mathematical analysis into a theory originating from set theory and axioms, as generalisable as possible and free from counterexamples. Subsequently the same approach had been then extended from analysis to other branches of mathematics, lead by the taste and desire for axiomatising and unifying all mathematics under the language of set theory. The feature that can be found in all books produced by Bourbaki any connection with the physical reality as well as the history motivating the given theorems are entirely omitted from the texts.

The MAB introduced in this section, is formalised *à la Bourbaki* in the next one, and subsequently in the pragmatic way in section 3.

2 The Bourbachist way

Definition 2.1. Let (Ω, \mathcal{A}) be a σ -algebra defined as a non-empty set Ω paired with a subset of its power set \mathcal{A} , containing the empty set, and closed under numerable union and complement set. Let this be called *action space*. Let $\mathcal{I}_K = \{1, 2, \dots, K\} \subset \mathbb{N}$ be a set of indexes whose generic element k is called *arm*, by convention. Let $\mathcal{I}_T = \{1, 2, \dots, T\} \subset \mathbb{N}$ be another set whose elements are called, again conventionally, *time*. Let \mathbb{R}_+ be the positive real axis including the zero.

The relationship between the above defined elements are given by a function A defined as:

$$\begin{aligned} A : \mathcal{I}_T \times \mathcal{A} &\longrightarrow \mathcal{I}_K \\ (t, \omega) &\longmapsto A(t, \omega) = A_t(\omega) \end{aligned}$$

and by a function \mathcal{R} , defined as:

$$\begin{aligned} \mathcal{R} : \mathcal{I}_T \times \mathcal{A} &\longrightarrow \mathbb{R}_+ \\ (t, \omega) &\longmapsto \mathcal{R}(t, \omega) = \mathcal{R}_t(\omega) \end{aligned}$$

Let the former be called *action* and the latter be called *reward*. Let

$$\begin{aligned} R : \mathcal{I}_T \times \mathcal{I}_K &\longrightarrow \mathbb{R}_+ \\ (t, k) &\longmapsto R(t, k) = R_t(k) \end{aligned}$$

be another function, defined as the only possible function making the diagram below commutative, for each $t \in \mathcal{I}$:

$$\begin{array}{ccc} \mathcal{A} & \xrightarrow{A_t} & \mathcal{I}_K \\ & \searrow \mathcal{R}_t & \downarrow R_t \\ & & \mathbb{R}_+ \end{array}$$

Let R_t be called again *reward*, and the difference between \mathcal{R} and R will be clear from the context.

We observe that \mathcal{R} maps the events of the σ -algebra, while R maps the corresponding indexes. This is an analogous of the definition of probability respect to the one of random variable and probability density function, for when the real axis is restricted to $[0, 1] \subset \mathbb{R}$.

Now we consider

$$\begin{aligned} \mathcal{Q} : \mathcal{I}_T \times \mathcal{A} &\longrightarrow \mathbb{R}_+ \\ (t, \omega) &\longmapsto \mathcal{Q}(t, \omega) = \mathcal{Q}_t(\omega) \end{aligned}$$

2 The Bourbachist way

and we call it the *estimated reward of the action ω up to time t* , for $\omega = A_t^{-1}(k)$ for a fixed $k \in \mathcal{I}_K$, with the corresponding function $Q : \mathcal{I}_T \times \mathcal{I}_K \rightarrow \mathbb{R}$. It follows that Q is defined as an application of the mean value in a Lebesgue space over (Ω, \mathcal{A}) , that is now a Borel σ -algebra⁴ as:

$$Q_t(\omega) = \mathbb{E} [R_\tau(k) \mid k = A_\tau(\omega) \quad \forall \tau \in \mathcal{I}_t] \quad \omega \in \mathcal{A} \quad t \in \mathcal{I}_T \quad (1)$$

and therefore

$$Q_t(k) = \mathbb{E} [\mathcal{R}_\tau(\omega) \mid \omega = A_\tau^{-1}(k) \quad \forall \tau \in \mathcal{I}_t] \quad t \in \mathcal{I}_T \quad k \in \mathcal{I}_K \quad (2)$$

As \mathcal{R} and R did, also Q and Q satisfies the commutativity of a diagram analogous to the one shown above. The notation can be simplified for brevity⁵ to:

$$Q_t(k) = \mathbb{E} [R_t(k) \mid A_t = k] \quad (3)$$

where the mean value is for all the time indexes up to t and where the domain values of A_t is clear from the context.

Definition 2.2. Let the *total reward* $Q_\infty : \mathcal{I}_K \rightarrow \mathbb{R}$ be the function

$$Q_\infty(k) = \mathbb{E} [Q_t(\omega) \mid \omega = A_t^{-1}(k) \quad \forall t \in \mathcal{I}_T] \quad k \in \mathcal{I}_K \quad (4)$$

or with the simplified notation as:

$$Q_\infty(k) = \mathbb{E} [R_t(k) \mid A_t = k] \quad (5)$$

So far we have been considering the reward and the total reward for a fixed choice of k . We can vary $k \in \mathcal{I}_K$ in function of the time index. So let \mathbf{k} be an element of

$$\mathcal{I}_K^T = \underbrace{\mathcal{I}_K \times \mathcal{I}_K \times \cdots \times \mathcal{I}_K}_{T\text{-times}}$$

or equivalently a function from \mathcal{I}_T to \mathcal{I}_K . Definitions 1 and 3 are so generalised to $Q_t : \mathcal{I}_K^T \rightarrow \mathbb{R}$ for $t \in \mathcal{I}_{\leq T}$, having defined $\mathcal{I}_{\leq T}$ any interval of positive integers between 1 and T , and

$$Q_t(\mathbf{k}) = \mathbb{E} [\mathcal{R}_\tau(\omega) \mid \omega = A_\tau^{-1}(\mathbf{k}_\tau) \quad \forall \tau \in \mathcal{I}_t] \quad \mathbf{k} \in \mathcal{I}_K^T \quad t \in \mathcal{I}_T$$

and therefore

$$Q_\infty(\mathbf{k}) = \mathbb{E} [\mathcal{R}_t(\omega) \mid \omega = A_t^{-1}(\mathbf{k}_t) \quad \forall t \in \mathcal{I}_T] \quad \mathbf{k} \in \mathcal{I}_K^T$$

⁴For a foundational perspective, see Bourbaki [Bou04a].

⁵The simplified notation is often the only notation appearing in engineering textbooks (e.g. Sutton [SB18]), although this would not allow you to understand the subtle formalisation of assigning to an event ω its index k . More tragically, if only the simplified notation is introduced, some may call that the concepts introduced before irrelevant and pedantic.

3 The Pragmatic way

The mean value computed with a Lebesgue measure, over the Borel space generated as the sets of images⁶ $\mathcal{R}_t(\omega)$ for all $\omega \in \mathcal{A}$ can be reformulated as:

$$Q_t(\mathbf{k}) = \frac{\sum_{\tau=1}^t R_\tau(\mathbf{k}_\tau) \mathbf{1}_{A_\tau=\mathbf{k}_\tau}}{\sum_{\tau=1}^t \mathbf{1}_{A_\tau=\mathbf{k}_\tau}}$$

where $\mathbf{1}_{A_\tau=\mathbf{k}_\tau}$ equals to 1 for when the event ω corresponding to \mathbf{k}_τ is mapped exactly to \mathbf{k}_τ through A_t , and 0 for any other event. Extending the time indexes up to infinity, and to justify the notations introduced above, where we used ∞ for the finite case, we have the following theorem:

Theorem 2.1. *Given a ring of infinite cardinality to which the time index t belongs, and an Hilbert module⁷ to which the vector \mathbf{k} belongs, it follows that*

$$Q_\infty(\mathbf{k}) = \lim_{T \rightarrow \infty} Q_T(\mathbf{k})$$

Proof. Direct consequence of the definition of Q_∞ generalised to the theorem hypothesis' extended structures. \square

We now consider the value \hat{k} that satisfies

$$\hat{k} = \arg \max_{k \in \mathcal{I}_K} Q_t(k) \quad \forall t \in \mathcal{I}_T$$

for a constant value for each time index, as in the definition 2 of Q_t . If you consider the possibility of varying the chosen arm k across time, and so if you are allowed to compare different images of the function A_t , then $\hat{\mathbf{k}}$ is defined as

$$\hat{\mathbf{k}} = \arg \max_{\mathbf{k} \in \mathcal{I}_K^T} Q_t(\mathbf{k}) \quad \forall t \in \mathcal{I}_T \quad (6)$$

Under the light of theorem 2.1, and with the given definitions, we can now call the so defined vector $\hat{\mathbf{k}}$ the *solution of the generalised multi-armed bandits problem*.

3 The Pragmatic way

The first reasonable thing to do is to create a playground or a benchmark, where a ground truth of the multi-armed bandit problem is known. With this tool, where to test a range of algorithms and parameters, we can select a dataset and test a range of algorithms and ideas.

⁶We consider the definition under the accordance with the axiom of choice as in the ZFC axiomatic set theory, in order to avoid *virages dangereuses*. See also Bourbaki [Bou04b] and [TZ82].

⁷An algebraic structure generalising Hilbert vector spaces over the now introduced ring of time indexes. See for example [Bou87].

Creating a Benchmark

We introduce the tool in a particular case, assuming each arm normally distributed, with mean sampled from a uniform distributions in the interval $[-3, 3]$ and the standard deviation sampled from a uniform distribution on the interval $[2, 3]$. A representation of these distribution is plotted in figure 1.

If the studied case is modelled with a different distribution, what is said in this section is still applicable simply adapting this benchmark to the intended situation.

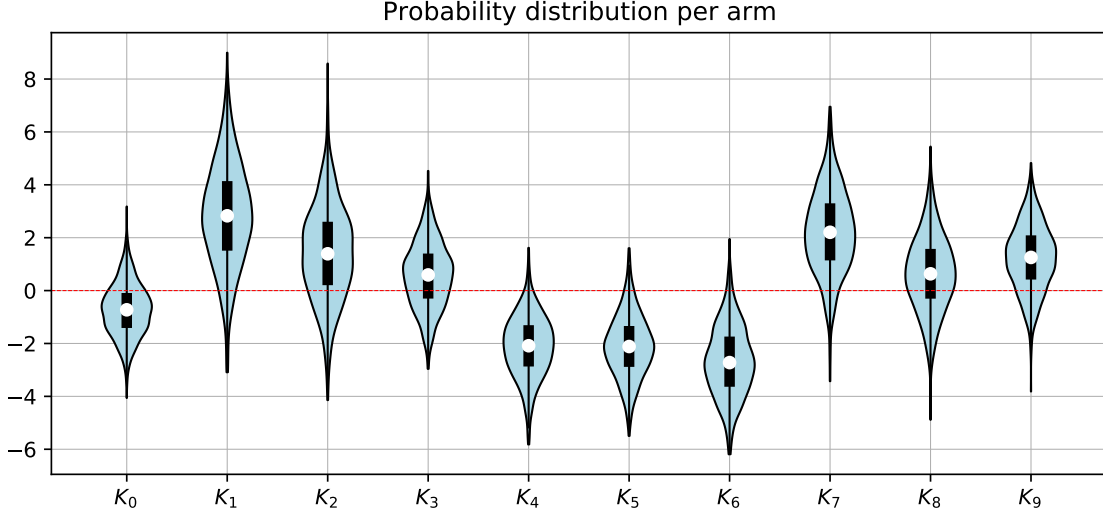


Figure 1: The distributions of the random reward for each arm K , unknown to the player, are sampled from normal distributions, with mean uniformly sampled in the interval $[-3, 3]$ and standard deviation in the interval $[1, 2]$.

Encoding the problem

The player gains a reward for after pulling an arm index k , for each time point t . We encode the rewards in a $T \times K$ *reward matrix* q . In our example $T = 1000$ is the time we will be pulling an arm and $K = 10$ is the number of arms. The element $q_{t,k}$ represents the reward collected for having pulled the arm k at the time-point t . As we can pull only one arm at a time, there is only one known value for each column of the matrix. All the other values are initialised to nan.

The multi-armed bandit is defined by two vectors μ and σ , where μ_k is the mean and σ_k is the standard deviation of the distribution of the arm k . To consider the non-stationary case, where the means and the standard deviations of the arms distributions represented in Figure 1 are not constant over time, we turns the vectors μ and σ into matrices of size $T_{\text{arm}} \times K$, providing the mean and standard deviation of the distribution

3 The Pragmatic way

of the arm k at time t .

The rewards can be accumulated for more or less numerous time points than T_{arm} , as the distributions of the arms can repeat. If $T_{\text{arm}} = 1$ then the problem is stationary, and if $T = 30$ and $T_{\text{arm}} = 15$ then each arm k will be looping over its parameters $\mu_{:,k}$ and $\sigma_{:,k}$ twice, according to:

$$q_{t,k} = \text{norm}(\mu(t \bmod T_{\text{arm}}, k), \sigma(t \bmod T_{\text{arm}}, k))$$

where $\text{norm}(\mu, \sigma)$ is the normal distribution of location μ and scale σ and \bmod is the modulo operator.

ϵ -greedy algorithms

In the previous section we created a benchmark and encoded the multi armed bandit response/rewards into a matrix.

Now we introduce the ϵ -greedy algorithms, a class of algorithms based on the idea that if your bad luck is consistent, probably it is not just bad luck. The player using these algorithms alternates between a phase of exploration (proportional to ϵ times), and a phase of exploitation (proportional to $1 - \epsilon$ times). In the first phase, the player acquires information about the structure of the problem regardless the immediate gain, and in the second one, the information gained are exploited to maximize the reward⁸.

The basic version of the ϵ -greedy algorithm (or *naïve ϵ -greedy*), selects a random arm when exploring and the arm that had obtained the best reward so far in the exploitation phase. This can happen after an initial phase of pure exploration, where only random arms are pulled. An example of the application of this algorithm is shown in figure 2.

A more sophisticated version the naïve ϵ -greedy is the *best reward ϵ -greedy*. In this case, instead of selecting any random arm in the exploration phase, we weight the random selection using the rewards obtained so far, excluding the arm with the highest reward. With this strategy we will be more likely to explore the arms that have provided good rewards in the past, and to refrain from spending money over an arm that have never provided any gain at all.

A third algorithm is the *least explored ϵ -greedy*. In the exploratory phase of this algorithm we increase the probability of falling over the least explored arms, instead of the one providing the highest reward. This method and the previous one are both aimed at preventing from getting stuck in a local minima, i.e. believing that the arm we are hitting is the best one, as it happens to provide a gain, though it is not the one with the optimal gain.

The fourth algorithm here presented is the *upper confidence bound ϵ -greedy algorithm* [SB18]. In this algorithm the estimated optimal arm at time t , is given by

$$\hat{k}_t = \arg \max_k \left[\hat{\mu}(k) + \lambda \sqrt{\frac{\ln(t)}{N_t(k)}} \right] \quad (7)$$

⁸An accurate historical introduction of this family of algorithms can be found at the end of chapter 1 of [SB18].

3 The Pragmatic way

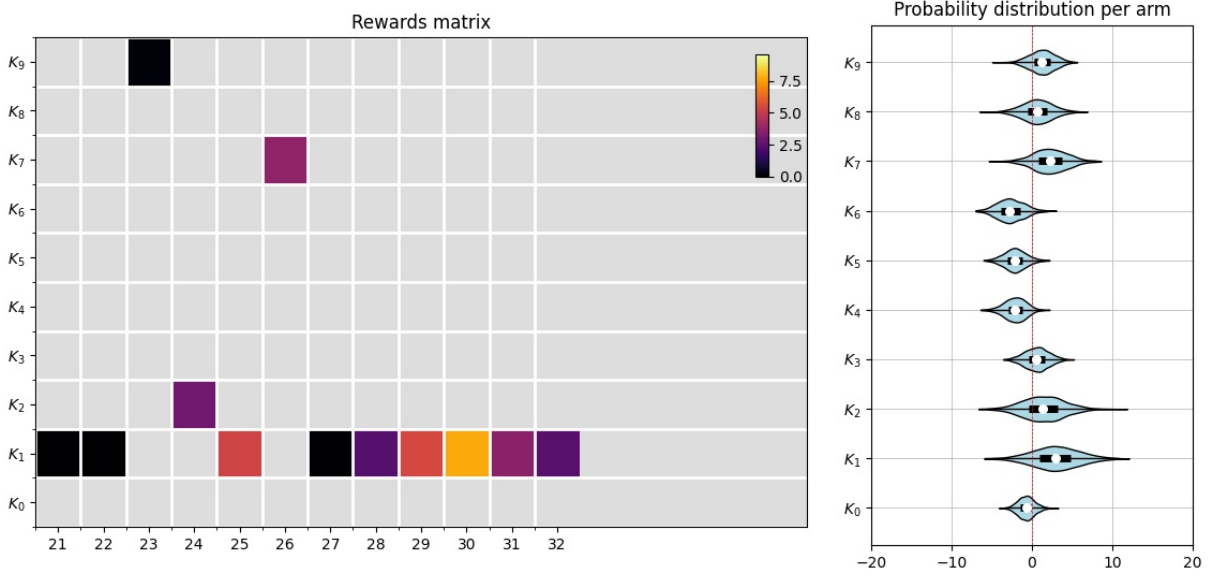


Figure 2: The reward matrix after 32 steps of a *naive* ϵ -greedy algorithm. We can see that step 23, 24 and 26 are explorations in a row of exploitation of the arm 7 that so far had produced the highest reward. To the grey colour corresponds the nan value used to initialise the reward matrix. In this instance, the reward is clipped at zero, as the loss of money is only the cost of pulling an arm at each time-point.

where $N_t(k)$ is the number of times the armed k had been pulled up to the time t , which can be easily computed from q . The regularisation term weights the uncertainty in the estimate, correcting for underestimation of the estimated mean.

Note that in this version of the game, the player will receive 0 when the sampled reward is below 0. This means that the estimated mean does not correspond to the one of the original distribution, though the result will be conservative in having an observed average close to zero for distribution whose mean is below the zero. You should resist the temptation of estimating the arm using the mode instead of the average in equation 7. In fact if the standard deviations are very different across arms, a very inconvenient arm, with the average below the zero, may be identified as the optimal one.

The performance of these algorithms are all depending upon the problem's distributions, and the optimal one should be found empirically via simulation. Providing a benchmarking for a general case would not be useful here. What provides the constraints to make the case less general, is based on the instance of the problem to which the algorithms are applied. A platform where to make further experiments is open-sourced and can be found at <https://github.com/SebastianoF/multi-armed-bandits-testbed>.

4 Comparing the two ways

The Bourbaki way presented in section 2 is based on an axiomatisation of the problem and it evolves from a functional and set-theoretical perspective. It focuses on the symbolism, and according to the Bourbachist tradition, it provides no examples or algorithms, as the only connecting point between the theory and the given problem is the axiomatic setting.

Assuming that section 2 is correct (excluding typos) and coherent (excluding Goedel⁹), it is easy to see that it had the side effect of turning a relatively simple problem into a complicated maze of interrelated concepts, whilst also pushing you away from the practical solution, and perhaps even entirely from mathematics.

On the contrary, the pragmatic approach of section 3 shows that there is no need to take a functional perspective, when a single matrix is enough. It shows that Borel spaces and Lebesgue Measures are not an important requirement. These tools have been developed in entirely different contexts to prevent counterexamples. There is also no need to extend the bibliography beyond one or two resources. Borel spaces and any element of measure theory are not just useless when aiming at a solution, they are also hindering creativity when facing a slightly different problem, as for example one with different types of distributions over time, or one where not all the arms are available at any point in time.

If you are in any doubt about this hindrance, you are invited to continue the formalisation started in section 2, to see how many pages and new definitions and diagrams are needed to formalise the case of arms whose distribution varies over time. You are also invited to implement the algorithm solving the problem having only the functional and algebraic definitions at hand rather than relying on the matrix point of view.

Other examples

Certainly the example provided is biased by the fact that it consists of the best approximation of a Bourbaki approach and of a pragmatic approach that I could attain. Also you may say, the MAB problem is not the ideal one to embed into the Bourbaki formalisation, as *per se* too empirical.

To answer these valid points, I wish to point out that the Bourbaki group intended to formalise the whole corpus of mathematics and that there are numerous cases of practical problems, whose pragmatic approach has been overly formalised¹⁰ as the one proposed here. These examples may also constitute a collection of case-studies for anyone who may believe that I had been over zealous in writing section 2 to cast a negative light upon the Bourbaki methodology.

The first most notable example belongs to the domain of optimal transport theory.

⁹In the article *The ignorance of Bourbaki* [Mat92] Mathias noticed that the Bourbaki attempt of grounding the whole corpus of mathematics in an axiomatic sense have happened after, and with a conscious effort to ignore the Goedel incompleteness theorems.

¹⁰Or *assiomatisation*, as Bruno de Finetti [DFN08] would have said playing on the Italian words *assiomi* and *matti*, crazy.

4 Comparing the two ways

From being a pragmatic tool of solve a class of optimisation problems, it had become, in the hand of Bourbachists, a 500 page book underpinned by a large amount of measure theory and Lebesgue spaces, perfectly irrelevant to solve any instance of an optimal transport problem. Comparing for example Hitchcock [Hit41] introduction to the formalised counterpart, written by Villani [Vil03] it is possible to see the Bourbachisations effects. The first work is easy to read, understand, implement and possibly extend in several directions by anyone having a high school mathematical education. The second one is a seemingly uncreated maze of unassailable interlinked concepts, requiring many years of academic studies only to grasp the first few pages, with no advantages in finding a numerical solution to the problem.

The second example of the Bourbachisation that I found is in the domain of medical image registration. The aim of this field is to solve the problem of finding the non-rigid deformation, or metamorphosis, between anatomies. The problem originates from the study of the growth and change of anatomical shapes by D'Arcy Thompson [d+42] and pragmatically extended, amongst others, by Modersitzki [Mod04]. The Bourbaki over-formalized branch can be found in works such as Younes [You10], where we have to wait for 12 chapters before seeing what had motivated the axiomatic mathematical theory developed up until that point. In this case too, there is no explanation of what the advantages of the axiomatic approach are in respect to the pragmatic one, which appeared half a century earlier.

You may now say, for this specific case, that the pragmatic approach [Mod04] does not use neither diffeomorphisms nor reproducing Kernel Hilbert spaces. While this is true, it is not proved that these two mathematical devices are resulting in anything more accurate than their pragmatic counterparts when implemented in practice. Instead it is true that they are computationally slower and that they increase the cognitive load.

The Bourbaki standards

There are other examples in the literature where we can find a comparison between the Bourbachist / pragmatic ways, such as algebraic topology, fuzzy logic and topological data analysis. Their detachment from the practical set of problems that had them originated, had turned them into convoluted axiomatic buildings, where it is not possible to find any breakthrough result, or even practical help, in the perspective of solving the problem given initially.

It is at this point evident the existence of a standardised pattern in the process of Bourbachisation: a problem solved by more than 50 years, and often in a very elegant and straightforward way, is taken under the wing of the academic axiomatisers and transformed into a list of definitions and theorems where no echo of the original problem motivating the theory can be found.

What is also a feature of the Bourbaki pattern is that the formalised version of the practical theory adds no value whatsoever. No new results having any practical relevance or impact can be found in the work by Bourbaki and their followers.

There is only one notable exception to this rule that we could find. The work Mochizuki [Moc12] is claimed to have solved the *abc conjecture*. Although, worth of

a pantomime, according to the mathematicians who had tried to read this work, “the proof is too impenetrable to be understood”¹¹.

The bright side of Bourbaki

I am not here to accuse Bourbaki. The evil that men do lives after them. I am writing these pages to try to analyse and understand the phenomenon beyond its name and its influence. It is true that, despite many have express their negative view about the Bourbachist’s mathematics¹², the Bourbaki approach is still widespread if not predominant across the academic community and also greatly valued and honoured¹³.

Very often, the over-axiomatization of a theory developed outside academia by scientists chasing practical problems, had received more recognitions than the original work. Highly valued and cited uber-bourbachists works are for example Grotedniek [Gro11] and the already mentioned four volumes of Mochizuki [Moc12]¹⁴.

For this reason, it is not true to claim that the Bourbachisation has no practical use. Below are itemized some points in favour of this approach, that are aimed at explaining the success of the Bourbachist way.

- *The outcome of the Bourbaki approach is inaccessible to neophytes*¹⁵, and it allows the existence of professors of mathematics who can not code or do not have any ability to solve any problem in practice. This seems to be the main reason that justifies the continuation of the Bourbachism, as neophytes usually are the people who have to decide where the public money goes and professors the ones who receives it.
- *The Bourbaki approach is good for the ego*. The pleasure of owning an elegant notebook filled with mathematical formulae written with a sharp pencil and a well thought after handwriting is a most sublime one. Unfortunately, after empirical evidence we can assure that this very same pleasure is a great obstacle in acquiring knowledge. The notebook owner, when facing a problem, will inevitably tend to

¹¹A statement published in Nature, Castelvechi [Cas15].

¹²Amongst the many: Arnold [Arn98], De Finetti [DFN08], Lockhart [Loc09], the already cited Mathias and its follow up [Mat98], Velupillai [Vel12]. And even the article by Marmier [Mar14], that sees the Bourbaki movement with enthusiasm and appreciation for their work and impact in the society, begs some questions when it says “Living mathematics is being done elsewhere in the world, in connection with new problems arising from other disciplines or other human activities”.

¹³To this regard, anyone is welcome to copy-paste section 2 and to extend it, in the Bourbachist style, into an article whose title could be something like *The multi-armed bandits for the working mathematician*, to see how this would be received by the community.

¹⁴It is also interesting to notice at this point the similarity between this work and the outcome of the randomized generator of maths paper at thatmathematics.com/mathgen/.

¹⁵An attempt of turning an over-formalised Bourbachist theory into something accessible for the layman, can be found in Villani [Vil12]. Interestingly enough, it seems that the only way the author could popularize his theory was to throw some unexplained formulas right before focusing the reader’s attention on some entirely unrelated autobiographical events. The result is even less accessible than the original work, proving that mathematicians can also be successful surrealist artists.

4 Comparing the two ways

abandon any scientific method and will bend the problem to the behold solution. To this regard, it would be interesting to measure scientifically the dopamine level of group of mathematician trying to solve a difficult problem respect to a group tweaking axioms to make the theory more abstract.

- *Bourbachism detaches mathematics from reality*, so it makes impossible to have any objective measurement of the quality or value of the work produced, besides the readers' opinion. This is a very unscientific feature, and again a very useful one for whoever must defeat more skilled competitors within the academic environment.

The advocates of the superiority of *pure mathematics*¹⁶ have even arrived at accusing the mathematics that have anything to do with reality of being more prone of making mistakes¹⁷. We can be reassured by the fact that under every circumstance, the reality is adamant to persist in being what it is, and it would be interesting to know what the authors would think of about someone advocating for detaching medicine and engineering from reality.

- *The Bourbaki inspired work are more generalizable*. While this appear to be true at first glance, we claim that on the contrary a Bourbaki theory is less generalisable. Simply adding a new or different assumption to the problem settings would require to re-write almost from scratch all the axiomatic building to include the new input in a generalisable manner. The pragmatic way provides handle on the problem that are easy to be tuned or re-adapted to a slightly different one.
- *Bourbachism binds the concepts in formal structures avoiding paradoxes and counterexamples*. This is a very valid point in favour of the Bourbachist method, as the concerns of mathematics with counterexample have led to various discoveries, from Galois theory, to Fractals, and the search for counterexample is a valuable tool to have a better understanding when exploring the limits of mathematical knowledge¹⁸. Although, the problem of the Bourbaki approach is the over-concern with counterexamples originating from theoretical considerations not related in any way to the sought solution. In section 2 we attained an algorithm that solves the problem, having never faced pathological counterexamples despite not relying on σ -algebras, Borel spaces, Lebesgue measures or even without explicit use of

¹⁶And with another footnote, I would like to notice that the academic dichotomy pure/applied maths is something that can not be found in mathematics before Bourbaki. You are invited to classify any of the work by Archimedes, Gauss, Euler, Lambert, Poincare or any other great name at any time in the history of pre-modern mathematics as *pure* or *applied* with no ambiguities. It is also worth mentioning that there are few French mathematicians, contemporary of Bourbaki, that had been labelled as *applied*, as Jean Leray, René Thom, Szolem Mandelbrojt (the uncle of Benoit Mandelbrot) for having left the group very early or for not having entered at all [BB84, Ati07].

¹⁷Gros [GST19] had found how even professional mathematicians can be mislead by reality. And they had leveraged on this most surprising fact, for advocating to increase the detachment. After concluding that “[...] we can’t reason in a totally abstract manner”, instead of suggesting to take into account the reality in the mathematical practice they suggested a move towards the opposite direction: “We have to detach ourselves from our non-mathematical intuition” [Sum19].

¹⁸For example Procesi [Pro77], Mandelbrot [Man83] and Gelbaum [GO03].

functions. What we came across were only some practical malices of the craft that are never learned by whoever is limiting themselves to the Bourbaki presentation of the problem ¹⁹.

5 In conclusion

If I wanted to divide the mathematical approaches into two, rather than Bourbaki and pragmatic, I would consider the Pythagorean and the Archimedean schools of thought. The Pythagorean school, started under the influence of the ancient Egyptian and Persian mathematicians, considers the mathematical practice as a tool to investigate and measure the reality and to find the connections between apparently distinct elements through abstraction and generalisation²⁰, starting from the investigation of the concept of number itself. The Archimedean vision sees mathematics as a tool to solve very practical problems, approaching them with heuristic, algorithms and even adhoceries²¹. To neither the Pythagorean nor the Archimedean belongs the dichotomy between pure and applied mathematics, as there is no concept of *pure* in the sense of detached from the reality, being the reality always the centre of the investigation.

The Bourbachist vision does not belong to any of these two mathematical categorisation, as it is neither oriented towards finding hidden connections between apparently separated phenomenon, nor towards solving practical problems. It is a relatively new trend, appeared at the horizon like a relict of the second world war, or as a post-modern fashion escaped from the art department, in which the manipulation of abstract structures arising from the need of generalisation had been twisted to its extreme. From searching for a solution, it had started wandering around the creation of abstract cathedrals where anything that is coherent with the initial axioms can be added, even if it does not solve a single problem or if it does not reveal any hidden connection between separate fields of science. The unavoidable consequence is that the abstract buildings built in this way are destined at becoming labyrinths without a centre, where the students will inevitably be waisting time and effort, better spend in learning to solve practical problems.

Only from the emergence of Bourbaki, the subdivision between pure and applied mathematics had become needed, as a line drawn between mathematical practice (either of Pythagorean or Archimedean school) and the academic axiomatisation of others

¹⁹About this last point in particular, there is an (in)famous case where over-concerned researchers had been misled by a misquoted counterexamples: the medical imaging paper by Lorenzi [LP13] claims that there is no bijective correspondence between the space of the tangent vector fields and the one of their integral curves. This claim is made after citing a very peculiar counterexample found in one of the Milnor research papers, involving the tangent space of the circle.

Interestingly enough the conditions for the counterexample to happen are never met in the applications presented in the paper itself, that deals with \mathbb{R}^3 . In this simple case, the tangent space of \mathbb{R}^3 is \mathbb{R}^3 and the bijective correspondence is guaranteed by the theorem of existence and uniqueness for ODEs.

²⁰As for example astronomy, music and architecture [Rob95], [BM11].

²¹An example of this approach is the proof of the formula for the parabolic segment's area by Archimede [BM11] and [Str19].

mathematicians solutions.

The comparison proposed in this paper, through the multi-armed bandit problem, aims at providing an example between the pure and applied approach towards the same problem, to reveal their strengths and limitations. It also collects a list of analogous cases in the literature, showing the axiomatisation pattern and investigating the reasons for the success of Bourbakchism.

Despite the fact that I am convinced that the students of the generations to come will be obliged to learn the Bourbaki sophistications to get a degree in mathematics, and to unlearn them as quickly as possible to be of any use to the non-academic society, I intended to show, alongside with many others before me (Mathias [Mat92], DeFinetti [DFN08], Velupillai [Vel12], Arnold [Arn98]), that the Bourbaki method is around for academic reasons, and it is not what mathematics is about.

References

- [Arn98] Vladimir I Arnol'd. On teaching mathematics. *Russian Mathematical Surveys*, 53(1):229, 1998.
- [Ati07] Michael Atiyah. Bourbaki, a secret society of mathematicians, 2007.
- [BB84] Anthony Barcellos and A Barcellos. Interview of bb mandelbrot. *Mathematical People. Birkhäuser, Basel*, 1984.
- [Bel56] Richard Bellman. A problem in the sequential design of experiments. *Sankhyā: The Indian Journal of Statistics (1933-1960)*, 16(3/4):221–229, 1956.
- [BM11] Carl B Boyer and Uta C Merzbach. *A history of mathematics*. John Wiley & Sons, 2011.
- [Bou87] Nicolas Bourbaki. Topological vector spaces, elements of mathematics. 1987.
- [Bou04a] Nicolas Bourbaki. Integration. Springer Berlin, 2004.
- [Bou04b] Nicolas Bourbaki. Theory of sets. Springer Berlin, 2004.
- [BR19] Djallel Bouneffouf and Irina Rish. A survey on practical applications of multi-armed and contextual bandits. *arXiv preprint arXiv:1904.10040*, 2019.
- [Cas15] Davide Castelvechi. The biggest mystery in mathematics: Shinichi mochizuki and the impenetrable proof. *Nature News*, 526(7572):178, 2015.
- [d+42] W Thompson d'Arcy et al. On growth and form. *On growth and form*, 1942.
- [DFN08] Fulvia De Finetti and Luca Nicotra. *Bruno de Finetti: un matematico scomodo*. Belforte, 2008.
- [GO03] Bernard R Gelbaum and John MH Olmsted. *Counterexamples in analysis*. Courier Corporation, 2003.

References

- [Gro11] Alexandre Grothendieck. Some aspects of homological algebra. 2011.
- [GST19] Hippolyte Gros, Emmanuel Sander, and Jean-Pierre Thibaut. When masters of abstraction run into a concrete wall: Experts failing arithmetic word problems. *Psychonomic bulletin & review*, 26(5):1738–1746, 2019.
- [Hit41] Frank L Hitchcock. The distribution of a product from several sources to numerous localities. *Journal of mathematics and physics*, 20(1-4):224–230, 1941.
- [Loc09] Paul Lockhart. *A mathematician’s lament: How school cheats us out of our most fascinating and imaginative art form*. Bellevue literary press, 2009.
- [LP13] Marco Lorenzi and Xavier Pennec. Geodesics, parallel transport & one-parameter subgroups for diffeomorphic image registration. *International journal of computer vision*, 105(2):111–127, 2013.
- [Man83] Benoit B Mandelbrot. *The fractal geometry of nature*, volume 173. WH free-man New York, 1983.
- [Mar14] Anne-Marie Marmier. On the idea of ‘democratisation’, ‘modern mathematics’ and mathematics teaching in france. *Lettera Matematica*, 2(3):139–148, 2014.
- [Mat92] Adrian RD Mathias. The ignorance of bourbaki. *Mathematical Intelligencer*, 14(3):4–13, 1992.
- [Mat98] ARD Mathias. Further remarks on bourbaki (a reply to criticism by professor sanford l. segal of the essay “the ignorance of bourbaki”). *Preprint*, 7, 1998.
- [Moc12] Shinichi Mochizuki. Inter-universal teichmüller theory i: Construction of hodge theaters, 2012.
- [Mod04] Jan Modersitzki. *Numerical methods for image registration*. Oxford University Press on Demand, 2004.
- [Pro77] Claudio Procesi. *Elementi di teoria di Galois*. Decibel, 1977.
- [Rob95] Gay Robins. Mathematics, astronomy, and calendars in pharaonic egypt. *Civilizations of the Ancient Near East*, 3:1799–1813, 1995.
- [SB18] Richard S Sutton and Andrew G Barto. *Reinforcement learning: An introduction*. MIT press, 2018.
- [Str19] Steven Strogatz. *Infinite powers: How calculus reveals the secrets of the universe*. Houghton Mifflin Harcourt, 2019.
- [Sum19] Article Summary. Expert mathematicians stumped by simple subtractions. <https://www.sciencedaily.com/releases/2019/07/190710103231.htm>, 2019.

References

- [Tho33] William R Thompson. On the likelihood that one unknown probability exceeds another in view of the evidence of two samples. *Biometrika*, 25(3/4):285–294, 1933.
- [TZ82] Gaisi Takeuti and Wilson M Zaring. Introduction to axiomatic set theory. Springer, 1982.
- [Vel12] K Vela Velupillai. Bourbaki’s destructive influence on the mathematisation of economics. *Economic and Political Weekly*, pages 63–68, 2012.
- [Vil03] Cédric Villani. *Topics in optimal transportation*. Number 58. American Mathematical Soc., 2003.
- [Vil12] C. Villani. Théorème vivant. 2012.
- [You10] Laurent Younes. *Shapes and diffeomorphisms*, volume 171. Springer, 2010.