From Arms to Trees: Opportunity Costs and Path-Dependence and the Exploration-Exploitation Tradeoff

Strategy Science

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Abstract

The literature on the exploration-exploitation tradeoff has anchored on the n-armed bandit problem as its canonical formal representation. This structure, however, omits a fundamental property of evolutionary dynamics. Contrary to a bandit formulation, foregoing an opportunity may negate the possibility of engaging in that opportunity in the future --- not just modifying the beliefs about the attractiveness of engaging in that opportunity. Thus, the bandit structure only incorporates path-dependence with respect to beliefs, and not with regard to capabilities as our usual conceptions of dynamics of learning and capabilities would suggest. Further, the consideration of opportunity cost is rather static and does not address the dynamic unfolding of opportunity structures. The nature of path-dependence and opportunity costs are used to frame many of our existing conceptualizations of search processes and firm dynamics, including bandit models, real options, pivoting, the "secretary problem", and "island" models of firm diversification. The discussion points to the need to develop canonical models of what evolutionary biologists' term phylogenetic trees and opens up a set of new questions, such as what is the degree of parallelism of trajectories that is possible within an organization, what is the fecundity of different trajectories in terms of likelihood of branching possibilities arising, how are these latent branching opportunities accessed?

It has now become well accepted that the exploration-exploitation tradeoff is central to how organizations, and social systems more broadly evolve and manage the dual challenges of both near-term and longer-term survival (Holland, 1975; March, 1991; Levinthal and March, 1993). The literature has converged on the n-armed bandit model as a canonical representation of this problem (Holland, 1975; March, 2003; Posen and Levinthal, 2012).[1] However, as elaborated below, the bandit model does not incorporate some fundamental features of the underlying motivating questions of navigating near-term and longer-term survival. First, most analyses do not incorporate a survival criterion and analyze the performance implications of alternative strategies and structures after some fixed history. Further, path-dependence is present in these models only in the form of beliefs over preferred actions. In this sense, the standard models focus on the learning dynamics of "know what", but not "know how". As Levinthal and March (1981) demonstrate, the dual process of learning about actions and learning how to act can result in competence traps. An organization may become highly skilled at less than desirable alternatives, and as a result even if the latently superior option is subsequently tried, it would appear in the immediate term as inferior to the current practice or strategy. Lastly, and the critical point developed here, the opportunity structure is treated as fixed ---- an alternative not chosen "today" could always be visited "tomorrow".[2]

[1] While the exploration-exploitation tradeoff was introduced to the management literature by March (1991) in a model of individual and collective learning, not a bandit model, and some have built directly on this model structure (Fang, Lee, and Schilling 2010), much of the subsequent work, including by March (Denrell and March (2001) and March (2003)) adopted the bandit model as a basis with which to examine this issue, a modeling structure with a long history in statistical decision theory (Gittins, 1979) and used explicitly by Holland (1975) to frame the exploration-exploitation tension.

[2] There is a line of modeling that considers change in the payoffs associated with a given alternative (arm) sometimes referred to as "restless bandits" (Whittle, 1998; Posen and Levinthal, 2012; Laureiro-Martinez, Brusoni, Canessa, and Zollo, 2015). While these models have some sense of path-dependence in that the value of the payoff associated with a given alternative may change over time, there is no path-dependence in the sense that not choosing an alternative in one period does not preclude its choice in another.

The issue of opportunity cost is central to the exploitation-exploration trade off and distinguishes it from more conventional analyses of investment. In the context of the exploration-exploitation tradeoff, "investment" is not some explicit capital expenditure but rather consists of engaging in some alternative action that current beliefs suggest may be inferior to other alternatives. Thus, central to the issue of the exploration-exploitation tradeoff is that learning is "on-line" (Gavetti and Levinthal, 2000). It is the presence of opportunity cost and on-line search that makes "neighborhood search" a possibly useful strategy as such a strategy balances the wisdom of current practices with the possibility of superior alternatives (March and Simon, 1958). However, the value of neighborhood search as a strategy depends on the degree to which there is some spatial correlation among alternatives (Levinthal, 1997). In the typical bandit model, alternatives are treated as being uncorrelated and hence the exploration-exploitation tradeoff is manifest by the degree to which beliefs as to what constitutes superior actions influence an actors' behavior. This relationship between "beliefs" and "actions" is attenuated by the specified search strategy and this relationship is typically modeled using the Softmax operator (Holland, 1975; Posen and Levinthal, 2012) with search being more or less exploitive (exploratory) to the degree that beliefs about superior alternatives are (less) determinative of behavior.

Path-Dependence

The sole carrier of path-dependence in a bandit model are beliefs, with the potential pathology of an actor prematurely locking into a less than optimal choice (Denrell and March, 2001). As Denrell and March (2001) highlight, the critical feature is that future sampling of alternatives is a function of current beliefs and, as result, beliefs that are "false negatives",

assessing a good alternative as being inferior, will not be corrected as these inaccurate beliefs will prompt the actor to avoid the mis-accessed alternative.[3]

In the evolutionary dynamics of organizations, a key property is the cumulative nature by which capabilities accrue over time (Penrose, 1958; Nelson and Winter, 1982). As noted above, incorporating a dual process of capability learning and belief learning may result in a "competence trap" (Levinthal and March, 1981). While a competence trap highlights the potential pathology of the dual process of learning "how" and learning "what", existing capability differences may lead firms to rationally make distinct choices in the face of uncertain payoffs (Wu, Wan, and Levinthal, 2014).

In addition to these dynamics of beliefs and capabilities, there is the question of the possible dynamics of the opportunity structure that an actor faces and possibly creates. In raising this issue of the possible dynamics of the set of alternatives, it is important to distinguish between a situation in which the payoffs to a given arm may change over time (Whittle, 1998; Posen and Levinthal, 2012) from a situation in which the availability of the alternatives themselves may have a temporal quality. As Davis et al (2009) note, strategic alternatives often have a fleeting quality to them.

In this respect, in the bandit formulations of the exploration-exploitation tradeoff, path-dependence in a more fundamental sense is absent in that in these formulations the latent opportunity structure is unchanging. Within a bandit like structure, if on Monday a certain choice was taken and outcome realized, the other *n-1* possibilities lie in wait on Tuesday, and Tuesday's choice has no impact on the possibility of action on Wednesday. This characterization may seem to trivialize the consideration by the use of days of the week to mark time periods; however, the

[3] In addition to "false negatives" possibly not be corrected, modest prior beliefs of actions that in fact have considerable merit may also stand uncorrected as a result of a process of endogenous sampling.

fundamental issue remains if one expresses the choice structure over time in more general terms as a "period". Such a dynamic seems apt for a decision such as what constitutes the best path and mode of transit by which to commute to work. The pain, pleasure, and time associated with the different possibilities can be sampled and revisited, with the choice of not engaging in a particular option in a given time period not precluding that possibility in a future time period.

However, this history invariant opportunity structure seems at odds with our usual conception of actors needing to "seize" opportunities. The notion that it is important to seize an opportunity presumably stems from a sense that an actor may be faced with some unique opportunity structure that may not, and indeed may be unlikely to, present itself again in the future. A latent entrepreneur coming of age at the dawn of the PC (cf., Gates [Microsoft], Jobs [Apple]), the internet (cf., Andreessen [Netscape], Case [AOL]), or ecommerce (cf., Bezos [Amazon], Omidyar [eBay]) may face a unique historical circumstance. If these actors decided to pass on that latent opportunity in some "period t" to experience further their current situation or some 3rd alternative, that latent opportunity would not necessarily be lying in wait for them at some future "period t+1". Further, seizing this opportunity will entail negating other latent choices, for some continuing with their education and for others existing employment, or again some alternative "outside option".

Rather than conceiving of exploration and exploration as a sampling problem, and again a sampling dynamic with no path-dependence with respect to the opportunity structure actors face, consider instead the sort of branching process that evolutionary biologists term phylogenetic trees, or sometimes more colloquially the "tree of life" (Dennett, 1995). The hierarchical nature of such "trees" indicate ancestry, while the branching connotes speciation events (May, 1942 and 1988). While in the biological context this branching is a random process of genetic variety in

conjunction with some possible happenstance of the particular niche space in which the new form arrives, in the organizational context such "branching" may reflect considerable intentionality. However, that intentionality may express itself in possibly unanticipated circumstances, as noted above in the different epochs of opportunity in information technology.

The entrepreneurs noted above moved into what have might be termed as the adjacent possible (Kauffman, 2000). Changes in the broader macro environment of technology and the business context made possible these initiatives (Levinthal, 1998), initiatives which just a few years prior would have not been feasible. Further, per the notion of a "window of opportunity", if they as latent entrepreneurs had waited, perhaps per the sensibility of the exploration-exploitation tradeoff not wanting to give up their current activity, that opportunity would soon pass --- either because other actors had moved to realize its potential, or if there was a substantial collective waiting of the full set of latent entrepreneurs, changes in technology and the business context may render the opportunity moot.

For our purposes, it may be better to relabel the "tree of life" a "tree of opportunities". More accurately, the "tree" reflects those opportunities that were realized --- presumably out a vast sea of latent opportunities. There is not some constant number of "arms" over which choice occurs, but an everchanging array of realized trajectories and latent opportunities. In addition, as is true in the case of phylogenetic trees in evolutionary biology, branches do not extend forever. A branch may terminate as the result of an extinction event --- and what we might think of in the business context less dramatically as an exit if we treat the branch as an initiative within the firm, or the demise of an industry if we consider organizational populations. Branches may also terminate with what evolutionary biologist would term a speciation event. A speciation event can take on two basic forms. One is akin to what discussions in entrepreneurship and lean startups

would term a "pivot" (Blank, 2003; Reiss 2011). There is an abrupt shift in the trajectory, but not the formation of distinct, independent branch. Alternatively, as is a common situation in the context of corporate entrepreneurial activity, the initiation of a new line of business is not necessarily tied to the termination of an existing business unit and thus the existing trajectory may persist with a branching event --- a new initiative that supplements prior initiatives.

One line of work on industrial dynamics and firm diversification does incorporate some elements of such a dynamic branching process (Sutton, 1998; Botazzi and Secchi, 2006; Klepper and Thompson, 2006; Klette and Kortum, 2004). The random arrival of new sub-markets in which a firm may participate is treated as a function of the existing sub-markets in which the firm operates. The resulting branching process is used to motivate the empirical regularities of firm growth rates and in particular Gibrat's Law of proportionate growth. While Klette and Kortum (2004) endogenize the rate of this branching process as a function of a firm's r&d expenditure, there is no explicit consideration of the choice to "seize" an opportunity as, while the "arrival" of the opportunity is treated as stochastic, the merit of the opportunity is treated as known.

Opportunity Cost --- and Parallelism

It is important to recognize that the critical factor that underlies the exploration-exploitation tradeoff is that of opportunity cost. Learning in this setting is online (Gavetti and Levinthal, 2000) --- information about the value of an alternative can only be generated by direct experience with it. Thus, experimenting with the novel comes at the opportunity cost of not benefiting from the familiar. In the absence of this opportunity cost, there would be not be an exploration-exploitation tradeoff, but rather a problem of search and sampling (cf., DeGroot,

1970). In a pure search problem, there is a direct cost of search or sampling, for instance the cost of a surveying a customer or running a laboratory experiment, but not an opportunity cost --- search on one option does not preclude the use of other options.

In a world of "trees" and not "arms", the issue of opportunity cost expresses itself as the degree of parallelism that is possible. That is, is the organization capable of sustaining current initiatives while engaging in a new initiative? In that regard, the question of the opportunity cost of search turns on a Penrose-like (1959) consideration of whether an organization's capability set has slack capacity to accommodate new initiatives. In this regard, as Levinthal and Wu (2010) point out, it is important to distinguish between those capabilities that are capacity constrained, such as a product development team or managerial time and bandwidth, versus capabilities that are scale-free, such as intellectual property or band-name. In addition, as Levinthal and Wu (2010) demonstrate the "shadow price" of capacity constrained capabilities has to be understood in the context of the markets in which those capabilities are applied. Thus, as a product market matures, the opportunity cost of their application in the current market context may decline, making the exploration of alternative possibilities, or branches, relatively more attractive.

More generally, the exploration-exploitation tension is modulated by the forces that constrain or facilitate parallelism within the organization. A new initiative that pulls a few engineers and managers in a new direction may be "exploratory" with regard to its novelty, but possibly pose modest opportunity cost on existing initiatives and in that regard have minimal impact on the organizations ongoing "exploitation" of its current initiatives.

The breadth of a corporate "tree" of activity is presumably a joint function of resource availability, the relative opportunity represented by each of the extant "branches", and the perceived promise of the latent new opportunities. Within the context of lean startups, it is

argued that the enterprise should focus on a single initiative at any point in time. In that setting, the need for focus is driven by the limited resources of the enterprise. If progress is to be made along a trajectory, the suggestion is that there need be a single trajectory. The link between progress and focus is not merely one of resources, but also the sense of "burning bridges" behind oneself by foregoing prior trajectories presumably acts as an important incentive (Shin and Milkman, 2016).

A more established enterprise can sustain some multiplicity of initiatives at any given time, however the constraints and opportunity costs of scare talent, time, and treasure are still present (Penrose, 1958; Levinthal and Wu, 2010). Because the formal modeling apparatus of the bandit model treats choice as being discrete, one of *n* options, the issue of the scale of activity is not present in discussions of the exploration-exploitation tradeoff. But the issue is not simply whether activity *i*, *j*, or *k* is present, but what is the allocation of capital and managerial time and bandwidth associated with each. Somewhat similarly, in the representation of phylogenetic trees in evolutionary biology, the "branch" represents the presence of a particular form, but there is generally no recognition in this schemata of the scale, or density, of forms.

Exploration and Exploitation in a World of Trees

How does the exploration/exploration tension play out in a world "trees"? Three basic considerations are highlighted: opportunity cost and the role of parallelism, the threshold of attractiveness that triggers a new initiative, and the shift to consider alternatives as being potentially being generative as well as ends in of themselves.

Threshold of initiation

Standard models of sequential search (DeGrot, 1970) postulate a sampling cost and the optimal search strategy entails searching until an alternative reaches some threshold value.[4] A different formulation of sequential search, less salient in the literature on statistical decision theory, but more proximate to the problem of branching and "trees" versus fixed arms, was developed under the label of the "secretary problem" (Freeman, 1983). Putting aside the dated label, the basic formulation of the search problem is as follows: A known number of items is presented one-by-one in a random order, with all *n!* possible sequences being equally likely. The actor engaged in the search process is able to rank the items that have so far been presented in order of desirability. As each item is presented, the searcher must either accept it, in which case the process stops, or reject it. If the search process continues until the last item is presented, that final alternative must be accepted. The search problem is to maximize the probability that the chosen alternative is the maximum of the latent alternatives.[5] Since the actor is never able to go back and choose a previously presented item which might in retrospect turn out to be the best, they have to balance the danger of stopping too soon and accepting an apparently desirable item with the possibility that an even better alternative might still yet to come.

The initial labeling of this search problem stems from its natural application to the problem of selecting applicants for a job, though clearly the structure maps onto a broad range of choice problems. As Davis, Eisenhardt, and Bingham (2009) suggest, new technological

[4] The parallelism between the optimal search strategy and a satisficing or aspiration-driven process is striking. Both the optimal and behaviorally postulated strategy entail search until a specified threshold is reached. The distinction is that in the case of the behavioral process, the threshold is postulated a priori or derived from a process of aspiration-driven learning, whereas the threshold associated with the optimal search strategy is derived based on the beliefs regarding the distribution of the values of the population of alternatives from which alternatives are drawn and the direct cost of search or sampling.

[5] Interestingly, the optimal strategy in this problem context also has an aspiration-like quality. After some initial period of sampling, a rank order threshold is specified such that the next alternative that meets or exceeds that rank is accepted (Freeman, 1983). Thus, the initial sampling is used to inform what might constitute a reasonable aspiration level.

opportunities tend to be fleeting. An organization may have an opportunity to take a specific action at a given moment in time, but that moment and the associated opportunity may pass. For instance, a venture capitalist may choose to invest or not in a specific deal, but after some brief decision window, that opportunity will cease to exist. However, given the issue of the possible constraints on parallelism, the pursuit of a particular opportunity may come at the cost of a limited capacity to pursue future opportunities. Complicating matters further, the successful realization of a given opportunity may generate additional resources that relax the possible constraints on parallelism within a given organization. Thus, there is a possible tension between the impulse to "keep one's powder dry" for possibly superior future opportunities and a bootstrapping like possibility of using prior successful initiatives to support future possible initiatives.

Options and Opportunity Generation

The strategy field has embraced the notion of real options as a central way by which a forward looking rationalistic approach links prior behavior to future possibilities (McGrath, 1997; Trigeorgis and Reuer, 2017). Initial investments in a so-called "stage 1" both lead to some degree of updating about the value of subsequent investment, but also lower the cost or make feasible the possibility of subsequent investment to realize an opportunity. As an illustration of the later property, perhaps some initial investments constitute the acquisition of some property rights over an asset, such as an oil tract, a movie screen play, or patent. In other settings, the cost of realizing an opportunity is lowered as a result of time compression costs (Dierickx and Cool, 1989; Hawk et al, 2013) such that by making antecedent investments in various capabilities subsequent states can be achieved with less cost than if they were approached in a more discrete

manner. More generally, the notion of privileged access to future states is central to the idea of "real options".

Less appreciated in the discussion of real options is the question of firm differences at the onset of what is taken to be the "stage 1" investment. If firms are effectively homogeneous a priori, with no propriety knowledge of the prospects of a given alternative and no distinctive capability or skills with which to access a particular set of alternatives, then the purchase of a real option would be akin to buying a lottery ticket. Essentially firms would be like a homogeneous consumer, each free to bet on any set of numbers in a lottery that they wish. Thus, real options are interesting not only in how an initial investment opens up a distinctive set of opportunities, but also in how a firm's existing position and capabilities change the value of alternative options. As an illustration of such considerations, Wu, Wan, and Levinthal (2014) show that established firms may chose to "bet" on technologies that appear inherently less promising if their existing capabilities are complementary to those technologies.

A firm's current set of actions, capabilities, and market position both constrain the achievable set of actions, capabilities, and market positions that may be obtained in subsequent periods and influence the payoffs as to what might constitute more or less desired positions. The past casts a shadow on the set of future possibilities. While evolutionary accounts highlight the constraints of past actions and investments, forward looking rational choice accounts highlight the flip-side of the constraints of path-dependence: how investments "today" may enable opportunities "tomorrow". This idea is core to the notion of real options in which initial stage setting investments provide privileged access to future opportunities. In the absence of path-dependence, there would be no need to consider real-options --- a contemporaneous, myopic view would suffice in such a setting. Thus, whether one takes a "glass half empty", backward-

looking approach that highlights the constraints that path-dependence imposes or the "glass half full", forward-looking approach of real options that highlights the enabling role of current actions, path-dependence is central to the consideration of either perspective.

Critical to the argument here is that an important feature of options is not merely their direct reward associated with realizing the particular opportunity present, but what subsequent opportunities that initial initiative may engender. Investing in a new technology may prove useful in the firm's immediate product markets, but may also open an array of new opportunities, a possibility that the literature on real options terms a compound option (Trigeorgis, 1997). Firms, however, may vary in the degree of foresight as to future possibilities, from an ex-ante belief in a wide array of possible applications as is true for many early stage initiatives such as in the context of nano-technology or bio-technology, to less conscious, less intentional instances such as Cattani's (2005) discussion of "pre-adaptation" in the case of Corning. Kim and Kogut (1996) introduce the notion of what they term "platform technologies", which for them are technological capabilities that serve as a basis for entry to a wide array of market. They observe how different technological trajectories within the semiconductor industry provided more or less rich set of future opportunities. In the framework developed here, these technologies have distinct phylogenetic trees with these trees varying in the fecundity of their branching possibilities.

Discussion

The exploration – exploitation tension is central to evolutionary dynamics (Holland, 1975). Our discourse in the strategy literature in some respects captures this fundamental truth. However, our more formal conceptualizations are argued to miss important elements of this

"truth". In our current modeling, prior choices influence the subsequent calculus of choice, whether because of changing beliefs (March, 1991) or a joint product of beliefs and capabilities (Levinthal and March, 1981). However, past actions not only influence the propensity to engage in future behaviors and the relative attractiveness of alternative courses of action, they also influence the possibility of those future behaviors. A door not open today, may not be present tomorrow. The idea of trajectories is core to an evolutionary economics perspective (Dosi, 1982). However, we tend to conceive of these trajectories as particular linear paths of descent. Trajectories not only offer potential paths forward, but movement down a particular trajectory may offer the opportunity of branching. This possibility of branching has been strongly embraced in our current discourse around start-up enterprises and the journey of pivots to possible success (Blank, 2003: Contigiani and Levinthal, 2019; Reis, 2014).

However, our more formal conceptual apparatus needs to catch-up and achieve a closer correspondence to the appreciative stories that we tell. The consideration of phylogenetic tress and branching processes is suggested to be a possibly a useful supplement to our consideration of sequential choice over a fixed set of "arms". What is the fecundity of latent branches off a given trajectory? How do organizations access and possibly engage these latent possibilities? What are the constraints on parallelism of trajectories within a single organization and what organizational practices might relax those constraints? The culling and cultivation of branches suggests that a core task of strategic management is the management of the firm's internal ecology of initiatives (Warglien, 1995; Lovas and Ghoshal, 2000; Levinthal and Marino, 2015; Levinthal, forthcoming). The current work takes us a modest distance down that path, but the hope is that it may serve as a catalyst to a possible branching point in our pursuit of these issues.

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