

# Evolutionary Selection of Modular Decision Architectures

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November 20, 2009

## Abstract

We study the evolutionary properties of decision processes. We show that in the presence of harmful mutations, a population of decision makers who possess an architecture consisting of hierarchically organized decision modules will have a strictly higher asymptotic growth factor than a population of decision makers with fully connected decision architecture. We also show that under imperfect precision of the architecture and cyclical fluctuations in the environment, conflict among the reference policies of modules arises as an evolutionary equilibrium. Finally, we show that economic models of multiple decision processes can be represented as examples of the modular hierarchy we investigate.

## 1 Introduction

In this paper we investigate the evolutionary selection of two stylized architectures for decision processes: i) a *unitary (U) architecture* in which one fully connected circuit always

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determines behavior and ii) a *modular hierarchical (MH) architecture* in which a supervisory module assigns control to one of two separate executive decision modules.

Our analysis is motivated by the recent interest of economists in the study of decision processes in environments where rational decision making, arguably, fares poorly.<sup>1</sup> In particular, this is the case for intertemporal choice in self-control environments, which has lead economists to formulate decision making models characterized by the interaction of different "actors", *multiple selves*, with conflicting models of behavior.<sup>2</sup> We show that these models have a representation in terms of the modular hierarchical decision processes studied in this paper.

The main results of this paper are as follows. Under a stable environment, but in the presence of deleterious mutations, we show that the *MH* has a strictly higher asymptotic growth factor than the *U* architecture. The *MH* architecture will thus outperform the unitary architecture in the long run starting from any initial condition. This is because the modular architecture is more robust with respect to the harmful effects of accumulating mutations. The *U* architecture is fully connected: a mutation in any part of the circuit will influence its overall performance level. The *MH* architecture, on the other hand, is only loosely connected: it will continue to operate nearly optimally in the presence of several kinds of harmful mutations.

We also compare the performance of the two architectures in the presence of cyclical fluctuations in the environment. Because of the different levels of connectedness, the two architectures will typically face a complexity-efficiency trade-off. In particular, a unitary architecture might expend more energy while being able to respond more precisely to fluctuations in the environment. Under these conditions, and in the presence of harmful

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<sup>1</sup>See for instance the surveys in Rabin (1998), Loewenstein and Prelec (1992), and Camerer (2009). On the methodological issues involved in modeling decision processes rather than choices and preferences, see Caplin and Schotter (2008).

<sup>2</sup>See Frederick, Loewenstein, and O'Donoghue (2002) for a survey of the empirical evidence. Some examples of multiple selves models are Thaler and Shefrin (1981), Laibson (1997), Bernheim and Rangel (2004), Benhabib and Bisin (2005), Fudenberg and Levine (2006), Loewenstein and O'Donoghue (2007), and Brocas and Carrillo (2008).

mutations, the relative performance of the modular architecture will depend on its precision level. Specifically, we show that if the precision of a *MH* architecture is above a critical level, it will outperform a unitary architecture of the same size starting from any initial condition. This is because the gain in fitness for the unitary architecture, due to increased accuracy, is more than offset by the loss in fitness due to increased energy consumption.

In addition, we show that under imperfect precision and cyclical fluctuations in the environment, conflict among decision modules and the corresponding heterogeneity in behavior among decision making processes is an integral part of an evolutionary equilibrium. Intuitively, in the presence of undetectable fluctuations in the environmental state, internal conflict serves as a diversification device. This is because a completely redundant, correctly specified model for the current state becomes a rigid, misspecified model in the event of an undetected environmental perturbation.

By subjecting decision processes to evolutionary selection, we emphasize local effects of heritable mutations. But are mutations really that important for the evolution of cognitive and behavioral processes in humans? Rather than surveying the nature-nurture question, we simply note that an affirmative answer is consistent with the fact that many cognitive and behavioral disorders have a prominent heritable component and that several disorders, in addition to being strongly heritable, are also associated with explicit structural and functional changes in certain brain regions.<sup>3</sup> The interested reader should refer to chapters 7 and 16 in Breedlove, et al. (2007) for an introduction to the subject.

In addition, it is important for our argument that there exist heritable mutations whose effects are localized only in certain regions of the brain. This is consistent with recent work in neurogenetics. First, there are heritable conditions such as synesthesia<sup>4</sup> that manifest in increased connectivity only in certain regions of the brain, such as the fusiform gyrus

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<sup>3</sup>Down, fragile X, autism, Asperger's, and Tourette's Syndrome, for instance, all have explicit genetic basis. The same is true for disorders like schizophrenia, panic, and depression.

<sup>4</sup>Synesthesia is a condition where stimulation of one sensory or cognitive pathway leads to automatic, involuntary experiences in a second sensory or cognitive pathway. In the most common type, grapheme-color synesthesia, individuals perceive letters and numbers as inherently colored.

for grapheme-color synesthesia, as opposed to globally. Second, there is growing evidence that gene expression—the translation of the genetic blueprint into a functional product—varies significantly across brain regions and is controlled by other genes<sup>5</sup>. Our mutation process can thus be interpreted as modeling heritable mutations in the genes regulating the expression and hence the contribution to the reference action profile of the genes located in the various modules of the brain.

We believe our results provide an evolutionary justification for the models of multiple decision processes explored by economists, and in particular for multiple selves models. Because modular hierarchies are a type of neural network and hence can serve as universal approximators, they can provide a common conceptual foundation for all of these models. This could potentially be very useful for identification and testing since variation across models corresponds only to variation in the objectives of decision modules within the same *MH* architecture.

## 1.1 Related literature

This paper is related to the *indirect evolutionary approach*, which subjects agents' preferences to the analysis of evolutionary selection in order to identify their fundamental characteristics. Robson and Samuelson (2009) comprehensively survey this literature. In this paper, however, we subject agents' decision processes, rather than their preferences, to the analysis of evolutionary selection. Decision processes become a natural unit of analysis when agents' rationality is relaxed to allow for behavioral decision making.<sup>6</sup> In particular, as we discuss in Section 4, several of the recent decision theoretic analyses of intertemporal choice (can be interpreted to) develop explicit models of decision processes.

Two recent papers, Dasgupta and Maskin (2005) and Netzer (2009), are closely related

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<sup>5</sup>Nadler et al. (2006) show that there are large differences in gene expression among different brain regions in various strains of inbred mice, while Monks et al. (2004) show that there is significant genetic inheritance of gene expression in human cell lines.

<sup>6</sup>See the papers by Rubinstein and Salant (2008) and Benhabib and Bisin (2008) in Caplin and Schotter (2008).

to our study as they also concentrate on the evolution of hierarchical decision processes. In both papers, however, hierarchical decision processes arise in response to very specific choice problems that the decision maker is supposed to have encountered during its evolutionary past. On the contrary, in our paper, hierarchical decision processes arise regardless of what choice problems the decision maker might encounter, suggesting that modularity might be relatively robust across decision problems. In addition, in Dasgupta and Maskin (2005) and Netzer (2009), no internal conflicts arise in equilibrium and those which are observed are explained as a remnant of our evolutionary past. In our paper, on the other hand, internal conflicts have a positive evolutionary value because they serve as diversification devices in the presence of undetectable fluctuations in the environment.

We restrict our analysis to the comparison of unitary architectures with the simplest modular architectures, those consisting of two executive and one controlling processes. In particular, in our set-up, each executive process selects a feasible reference course of action. The controlling module then processes both feasible actions and chooses one of the two. This particular class of decision making architectures often arises in artificial life simulations, see for instance Cangelosi, Parisi, and Nolfi (1994), where a controlling unit evolves to monitor internal and external states and to assign control to one of the executive processes. Furthermore, this class of hierarchical architectures fits well with recent models and data on cognitive control developed in neuroeconomics.<sup>7</sup> In particular, hierarchical architectures can represent the interaction between the prefrontal cortex and the anterior cingulate cortex. Miller and Cohen (2001) provide theory and evidence that distinct areas in the human brain are associated with the monitoring of conflict and the execution of action. The anterior cingulate cortex (ACC) appears to be involved primarily in the monitoring of cognitive conflict. However, the ACC does not appear to be directly involved in executive functions. Rather, it exerts influence by activating other regions, such as the dorsolateral prefrontal cortex, which are ultimately responsible for adjustments in behavior.<sup>8</sup> In the context of intertem-

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<sup>7</sup>See Glimcher (2003) and Camerer, Loewenstein, and Prelec (2005) for general surveys of the field.

<sup>8</sup>See also, Kerns, Cohen, MacDonald III, Cho, Stenger, and Carter (2004).

poral choice, evidence for decision processes based on the interaction between the prefrontal cortex and the anterior cingulate cortex is presented by McClure, Laibson, Loewenstein, and Cohen (2004).<sup>9</sup>

Finally, our analysis is related to the recent literature on *kludges*<sup>10</sup>—see Ely (2007) and Marcus (2008). A *kludge* is a "marginal adaptation which compensates for, but does not eliminate fundamental design inefficiencies" in brain processes - from Ely (2007). Modular decision architectures, in our analysis, can in fact be interpreted as a kludge.

## 2 Set-up

Consider a decision-making architecture embedded in an agent that is a member of an age-structured population with a reproductive life lasting  $n$  periods. We keep the standard practice in age-structured models and treat a period of chronological time and an age class as equivalent. For each age  $i = 1, \dots, n$ , let the environment in a given state be denoted by  $s(i) \in S$ . The vector  $\varsigma = (s(1), s(2), \dots, s(n))$  denotes the environment during the agent's life, which is an element of some metric space  $S^n$  endowed with a norm  $d$ . In any environment  $s(i) \in S$ , a *decision-making architecture* (DA) executes an action  $a$  from a given set  $A$ , endowed with the norm  $w$ .<sup>11</sup>

Let  $\mathbf{a}_*^\varsigma = (a_{*,1}^{s(1)}, \dots, a_{*,n}^{s(n)}) \in A^n$  denote the action profile with the lowest asymptotic fitness loss (relative to the maximum) in environment  $\varsigma$ . Let  $L_\varsigma(\mathbf{a}, \mathbf{a}_*^\varsigma)$  be the asymptotic loss associated with any profile  $\mathbf{a} \in A^n$ .<sup>12</sup> Our goal is to examine the asymptotic growth factors of the two decision architectures, unitary ( $U$ ) and modular hierarchical ( $MH$ ), in the presence of fitness reducing mutations. In the  $U$  architecture, one single choice process determines the mapping between  $S$  and  $A$  for each age. In the  $MH$  architecture, multiple,

<sup>9</sup>But see Glimcher, Kable, and Louie (2007) for a skeptical view of these results.

<sup>10</sup>Sometimes also referred to as *kluges*.

<sup>11</sup>Note that the unit of analysis in our context is an architecture rather than an agent, a decision-making architecture and not a decision maker.

<sup>12</sup>The function  $L_\varsigma$  will typically be a monotonically increasing function of the distances  $w(a_i, a^{s(i)})$ . However, we do not require that to be the case.

nearly decomposable, decision modules interact to produce a map between  $S$  and  $A$ . Next, we formally describe the decision process of each architecture.

**Unitary Architecture.** Let  $\mathbf{a}^{U,\varsigma}$  denote the hereditarily acquired action of a unitary architecture in environment  $\varsigma$ . If profile  $\mathbf{a}^{U,\varsigma}$  is executed, the asymptotic fitness loss of the organism will be given by  $L_\varsigma(\mathbf{a}^{U,\varsigma}, \mathbf{a}_*^\varsigma)$ . In the long run, DAs that have the correct reference model,  $\mathbf{a}_*^\varsigma$ , for the environment  $\varsigma$ , will dominate the population.

**Modular Hierarchical Architecture.** Let a DA consist of two stage-one modules (modules 1 and 1') and one stage-two module (module 2). Each stage-one module has its own choice profile, namely  $\mathbf{a}_1^\varsigma = (a_{11}^{s(1)}, \dots, a_{1n}^{s(n)})$  and  $\mathbf{a}_{1'}^\varsigma$ . The same is true for module 2, which has a profile given by  $\mathbf{a}_2^\varsigma$ . For age  $i$  and state  $s = s(i)$  in environment  $\varsigma$ , module 2 allocates control to either module 1 or 1' by solving

$$\max_{a \in \{a_{1i}^s, a_{1'i}^s\}} -w(a, a_{2i}^s).$$

Basically, module 2 allocates control to the executive module whose action is closer to the reference action of module 2. Let  $\mathbf{a}^{H,\varsigma}$  be the solution to such a problem. The asymptotic fitness loss will be minimal for any DA with  $\mathbf{a}^{MH,\varsigma} = \mathbf{a}_*^\varsigma$ . This can be achieved if:

- (i)  $\mathbf{a}_*^\varsigma = \mathbf{a}_1^\varsigma = \mathbf{a}_{1'}^\varsigma$ , for any feasible profile  $\mathbf{a}_2^\varsigma$ ;
- (ii)  $\mathbf{a}_*^\varsigma = \mathbf{a}_j^\varsigma \neq \mathbf{a}_k^\varsigma$  for  $j = 1$  or  $1'$ ,  $k \neq j$  and  $a_{2i}^s$  is closer to  $a_{ji}^s$  than to  $a_{ki}^s$  for every state  $s$  in  $\varsigma$  and every  $i$ .

Hence for the modular hierarchy to survive in a stable environment, we need at least one of the module 1 actions to minimize fitness loss and the action of module 2 to be closer to the fitness minimizing action than the action associated with the other executive module.

Figure 1 provides an illustration of the difference between the two types of decision architectures. In the unitary architecture, all 6 hidden layer nodes, each of which could be a network in itself, are interconnected with each other. The architecture's response to a signal is thus determined through an interaction among all nodes in the hidden layer.

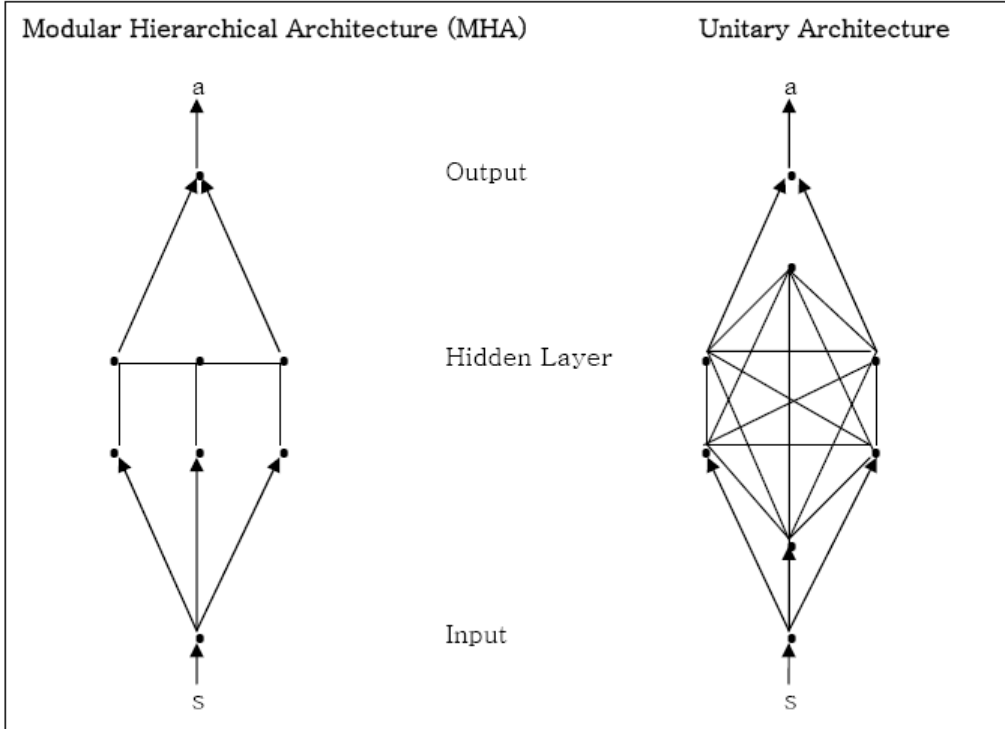


Figure 1: *Example of a unitary and a modular hierarchical decision architecture with 3 input, 2 output connections, and 6 hidden layer nodes. Undirected edges represent connections in both directions.*

More importantly, a change at a particular node, *ceteris paribus*, will always influence the architecture’s overall response since that node is connected to every other node in the hidden layer.

The *MH* architecture on the other hand is only sparsely connected. The left and right side columns in the hidden layer correspond to the two executive modules responsible for the architecture’s eventual response. The middle column is the controller that aggregates all information—the input signals and the recommended policy by each executive module—and allocates control to one of the nodes with output connections. The difference here is that there are direct connections among nodes within a module on a given level of the hierarchy but not across modules on the same level—they interact through the higher level controlling module. The *MH* architecture is thus nearly decomposable in the sense that changes at a

particular node, *ceteris paribus*, need not have global implications for behavior.<sup>13</sup>

Finally, note that for the same number of hidden layer nodes, there are 5 bilateral connections in the *MH* architecture versus 16 in the unitary. If operating and maintaining connections requires energy, the *MH* architecture will be much more energy efficient. On the other hand, the unitary architecture may exhibit much more sophisticated behavior since the greater number of connections allows for more nonlinear transformations of the input signals. This complexity-efficiency trade-off is at the heart of the results derived in section 3.2.

### 3 Evolutionary selection

In order to determine which architecture is more likely to be evolutionary successful, we subject them to mutations. The architecture which has a higher asymptotic growth factor under these conditions will thus be more likely prevail in the long run. We study evolutionary selection for unitary *vs.* modular hierarchical architectures in the presence of deleterious mutations i) under a stable environment and ii) in the presence of small cyclical fluctuations in the environment.

For each age  $i = 1, \dots, n$ , with the environment in a given state  $s(i) = s \in S$ , a *decision-making architecture* of type  $K = U, MH$  executes an action  $a^K$  from the given set  $A$ . Let  $G_i^K(m, s)$  denote the expected number of surviving offsprings from an agent of age  $i$  with decision architecture  $K$  in state  $s$ , that has  $m$  deleterious mutations in its executive process.<sup>14</sup> Also, let each agent of age  $i$  survive with probability  $P_i^K(m, s)$  if  $i < n$ , and with probability 0 if  $i = n$ . Hence  $G_i^K(0, s)$  and  $P_i^K(0, s)$  are the expected number of offspring and survival probability associated with the optimal action  $a_{*,i}^s$ . Each architecture is endowed with a measure of *precision*: we say that architecture  $K$  has *precision*  $\frac{1}{\phi^K}$  if it responds (changes its behavior) to the difference between two arbitrary states  $s, s' \in S$  only when their distance

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<sup>13</sup>For a thorough discussion of nearly decomposable architectures see Simon (1996).

<sup>14</sup>The expectation here is taken over some distribution of idiosyncratic individual shocks which average out in a sufficiently large population.

is larger than  $\phi^K$ : only when  $d(s, s') \geq \phi^K$ .<sup>15</sup>

Let  $q$  be the per period probability with which a harmful mutation occurs in a hidden-layer node. A mutation changes the reference action profile of the module in which it occurs. Since mutations are rare events, we assume that  $q$  is sufficiently small so that multiple mutations per period can be ignored.<sup>16</sup> In addition, since the vast majority of mutations are harmful (there are many more ways to increase than decrease the fitness loss), the probability of a reversal (a mutation in the direction of the loss minimizing action),  $r$ , will typically be even smaller:  $r \leq q$ .

The effect of deleterious mutations is as follows:

- every time a deleterious mutation accumulates in an executive process, the expected number of surviving offsprings,  $G_i^K(m, s)$ , resulting from executing the changed action profile is reduced for any  $i$  and any  $K$ . Thus  $G_i^K(m, s)$  is *decreasing* in  $m$ .
- every time a deleterious mutation accumulates in an executive process, the expected survival probability of the DA,  $P_i^K(m, s)$ , resulting from executing the changed action profile is reduced for any  $i$  and any  $K$ . Thus  $P_i^K(m, s)$  is also *decreasing* in  $m$ .
- mutations are inherited;
- a DA can carry on a total-executive and supervisory processes included-of at most  $W$  deleterious mutations: the accumulation-hereditary or not-of  $W + 1$  deleterious mutations is lethal.

Furthermore, a complexity-efficiency trade-off will determine each architecture's relative fitness. For a given energy endowment, the more energy consuming an architecture is, the smaller will be, other things equal, the number of its offsprings and its survival probability.

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<sup>15</sup>Essentially, this is a measure of how well the organism can separate the fundamental change due to a change in the environmental state from the noise generated by the idiosyncratic shocks at the individual level.

<sup>16</sup>This is consistent with the standard model of Luria and Delbrueck (1943) where mutations are spontaneous events independent of the environment.

That is, for given  $i, m$ , and  $s$ ,  $G_i^K(m, s)$  and  $P_i^K(m, s)$  will be smaller for the more energy consuming  $K$ . On the other hand, the architecture with the higher energy consumption will be responding more precisely to fluctuations in the environmental state  $s \in S$ . Specifically, the more energy consuming an architecture  $K$  is, the higher its precision  $\frac{1}{\phi^K}$  will be.

As noted before, the crucial distinction between unitary and hierarchical decision-making architectures is that the  $U$  architecture is fully connected, while the  $MH$  is only sparsely connected. Our reading of the literature on energy budgeting of the human brain<sup>17</sup> leads us to formulate the following implications of the different levels of connectedness for survival and precision.

**Assumption 1.** *A complexity-efficiency trade-off characterizes the  $U$  and  $MH$  architectures:*

1. *the  $MH$  architecture is more energy efficient*

$$G_i^{MH}(m, s) \geq G_i^U(m, s) \text{ and } P_i^{MH}(m, s) \geq P_i^U(m, s), \quad \text{for any } i, m, \text{ and } s;$$

*while, on the other hand,*

2. *the  $U$  architecture is more precise*

$$\frac{1}{\phi^U} \geq \frac{1}{\phi^{MH}}.^{18}$$

*We say the the complexity-efficiency trade-off is non-trivial if the inequalities hold*

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<sup>17</sup>For a summary of recent studies on the energy budget of the human brain see Raichle and Gusnard (2002) and the references therein.

<sup>18</sup>Attwell and Laughlin (2001) for instance estimate that over 3/4 of the brain's energy consumption is used for signalling among neurons. For a given number of nodes (neurons) in a network, an architecture like  $U$  with a large number of connections among those nodes will need to generate and maintain a large number of signals and will thus consume more energy than a sparsely connected architecture with the same number of nodes. Given the same action profile and the same initial amount of resources, the unitary architecture will consume more energy, which will result in  $G^U < G^{MH}$  and the same for  $P$ .

On the other hand, the unitary architecture allows for a greater number of nonlinear transformations of any input which, given the universal approximation results by Hornik, Stinchcombe, and White (1989, 1990), suggests that it should be able to approximate more precisely the loss minimizing policy with respect to small perturbations in the environmental state.

*strictly.*

We will also make a simplifying assumption that is not necessarily realistic.

**Assumption 2.** *Mating is assortative in the sense that like types match with each other in order to reproduce.*

This assumption allows us to ignore the complicating effects of sexual reproduction since with assortative mating, sexual reproduction is akin to asexual reproduction. We recognize however, that assortative mating may be violated, especially among types which do not exhibit any variation in behavior. In the appendix, we thus consider the opposite extreme of random mating. This is the best possible scenario for the  $U$  architecture since random mating dilutes the effects of deleterious mutations. Nevertheless, we are able to provide a sufficient condition under which all of our results hold locally around any steady state. This sufficient condition is essentially a stronger version of the condition for  $G_i$  in Assumption 1. With random mating, we need the efficiency advantage of the  $MH$  architecture to be sufficiently pronounced so that it overcomes the fact that with random mating, the  $U$  population will, in the long run, be dominated by males with 0 mutations, while for the  $MH$  architecture, since some mutations are fitness-neutral, that will not be the case.

### 3.1 Stable environment

We are now ready to study evolutionary selection of the two architectures. We first perform the exercise in a stable environment. We shall study cyclical variations of the environmental state in the following section.

**Assumption 3-s.** *The environment is stable,  $s(i) = s \forall i$ ; that is,  $s(i)$  does not vary over the lifetime  $i = 1, \dots, n$  of any agent.*

We can then drop reference to the environmental state  $s$  in the notation of this section, without loss of generality. Consider first the  $MH$  architecture. Let  $N_{i,t}^{j,k,l}$  denote the size at time  $t$  of the subpopulation of processes of age  $i$  characterized by a total of  $j + k + l$  mutations, with  $j$ ,  $k$ , and  $l$  mutations in each module. For expositional clarity, we consider

the case with 2 age classes (two period life), and 2 maximum mutations ( $n = W = 2$ ).<sup>19</sup> In this case the population structure vector at the beginning of period  $t$  is given by  $\mathbf{N}_t = [N_{1,t}^{0,0,0}, N_{2,t}^{0,0,0}, N_{1,t}^{1,0,0}, N_{2,t}^{1,0,0}, N_{1,t}^{1,1,0}, N_{2,t}^{1,1,0}, N_{1,t}^{2,0,0}, N_{2,t}^{2,0,0}]^T$ . For the *MH* architecture, we need to consider the distribution of mutations across the decision modules. This is because an architecture with two deleterious mutations in the same module will continue to operate optimally regardless of which module is affected. On the other hand, an architecture with one mutation along any two of the three decision modules may select a suboptimal course of action.<sup>20</sup>

The dynamics of the population of *MH* processes are governed by the linear system

$$\mathbf{N}_{t+1} = A^{MH} \mathbf{N}_t,$$

where, assuming each module is equally likely to mutate,  $A^{MH}$  is the  $8 \times 8$  nonnegative

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<sup>19</sup>All result are proved, however, for the general case of arbitrary  $n$  and  $W$ .

<sup>20</sup>If module 1 has the correct action while modules 1' and 2 have 1 deleterious mutation each, we have  $w(a_{1i}^s, a_{2i}^s) \geq w(a_{1'i}^s, a_{2i}^s)$  for each age  $i = 1, \dots, n$ . In all proofs, we will bias the scenario against the success of the MH architecture by assuming that whenever  $w(a_{1i}^s, a_{2i}^s) = w(a_{1'i}^s, a_{2i}^s)$ , the less optimal action is executed.

projection matrix given by

$$A^{MH} = \begin{bmatrix} (1-q)G_1(0) & (1-q)G_2(0) & rG_1(0) & rG_2(0) \\ (1-q)P_1(0) & 0 & rP_1(0) & 0 \\ qG_1(0) & qG_2(0) & (1-q-r)G_1(0) & (1-q-r)G_2(0) \\ qP_1(0) & 0 & (1-q-r)P_1(0) & 0 \\ 0 & 0 & (\frac{2q}{3})G_1(1) & (\frac{2q}{3})G_2(1) \\ 0 & 0 & (\frac{2q}{3})P_1(1) & 0 \\ 0 & 0 & (\frac{q}{3})G_1(0) & (\frac{q}{3})G_2(0) \\ 0 & 0 & (\frac{q}{3})P_1(0) & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ rG_1(0) & rG_2(0) & rG_1(0) & rG_2(0) \\ rP_1(0) & 0 & rP_1(0) & 0 \\ (1-q-r)G_1(1) & (1-q-r)G_2(1) & 0 & 0 \\ (1-q-r)P_1(1) & 0 & 0 & 0 \\ 0 & 0 & (1-q-r)G_1(0) & (1-q-r)G_1(0) \\ 0 & 0 & (1-q-r)P_1(0) & 0 \end{bmatrix}.$$

where the apex  $K = MH$  is dropped for notational simplicity.

Consider for example the elements of row 5, which represent the inflow during period  $t$  into the type  $N_1^{1,1,0}$ . A fraction  $q$  of the processes of type  $N_i^{1,0,0}$  mutate during period  $t$ . For  $2/3$  of these, the second mutation happens in a different module. As a result, these processes select a suboptimal action and leave surviving offsprings of  $G_i(1)$ . Next consider processes of type  $N_i^{1,1,0}$ . During period  $t$ , a fraction  $q$  develop a third deleterious mutation and die without leaving any offspring. In addition, for a fraction  $r$ , one of the deleterious mutations is reversed and they become type  $N_i^{1,0,0}$ . The remainder,  $(1-q-r)N_i^{1,1,0}$ , do not undergo any change and produce a number of descendents given by  $G_i(1)$ . Finally, since the

probability of more than one mutation per period is essentially zero, there is no direct inflow from any other type of process.

We next consider the unitary architecture. In this case, every deleterious mutation will influence the action profile of the decision process. Moreover, we do not need to keep track of the distribution of mutations, only of the total number. However, in order to make the projection matrices of the two architectures of the same dimension, we will use the same population structure vector for the unitary architecture<sup>21</sup>. The dynamics for a population of unitary processes are then governed by

$$\mathbf{N}_{t+1} = A^U \mathbf{N}_t,$$

where the projection matrix, assuming the values under the optimal action are still denoted by  $G_i(0)$  and  $P_i(0)$ , is given by

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<sup>21</sup>Any partition of the hidden-layer nodes of the unitary architecture into sets of nodes with equal number as the MHA will do.

$$A^U = \begin{bmatrix} (1-q)G_1(0) & (1-q)G_2(0) & rG_1(0) & rG_2(0) \\ (1-q)P_1(0) & 0 & rP_1(0) & 0 \\ qG_1(1) & qG_2(1) & (1-q-r)G_1(1) & (1-q-r)G_2(1) \\ qP_1(1) & 0 & (1-q-r)P_1(1) & 0 \\ 0 & 0 & (\frac{2q}{3})G_1(2) & (\frac{2q}{3})G_2(2) \\ 0 & 0 & (\frac{2q}{3})P_1(2) & 0 \\ 0 & 0 & (\frac{q}{3})G_1(2) & (\frac{q}{3})G_2(2) \\ 0 & 0 & (\frac{q}{3})P_1(2) & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ rG_1(1) & rG_2(1) & rG_1(1) & rG_2(1) \\ rP_1(1) & 0 & rP_1(1) & 0 \\ (1-q-r)G_1(2) & (1-q-r)G_2(2) & 0 & 0 \\ (1-q-r)P_1(2) & 0 & 0 & 0 \\ 0 & 0 & (1-q-r)G_1(2) & (1-q-r)G_1(2) \\ 0 & 0 & (1-q-r)P_1(2) & 0 \end{bmatrix}.$$

Under a stable environment, the advantage of the  $U$  architecture in terms of precision (Assumption 1) has no effect on fitness. The  $MH$  architecture cannot do any worse than the  $U$ . In fact it does strictly better, as summarized in Proposition 1.

**Proposition 1.** *In the presence of a complexity-efficiency trade-off (Assumption 1), assortative mating (Assumption 2), and a stable environment (Assumption 3-s), the  $MH$  architecture has a strictly higher asymptotic population growth factor than the unitary architecture starting from any non-zero initial condition. Furthermore, this is the case even if*

$$G_i^{MH}(m) = G_i^U(m) = G_i(m) \text{ and } P_i^{MH}(m) = P_i^U(m) = P_i(m).$$

**Proof:** Consider without loss of generality the case in which  $G_i^{MH}(m) = G_i^U(m) = G_i(m)$  and  $P_i^{MH}(m) = P_i^U(m) = P_i(m)$ . The dynamics of the two populations,  $U$  and  $MH$ , are governed, respectively by  $\mathbf{N}_{t+1} = A^U \mathbf{N}_t$  and  $\mathbf{N}_{t+1} = A^{MH} \mathbf{N}_t$ . The Perron-Frobenius theorem for nonnegative matrices implies that the asymptotic growth factor of each population is governed by the spectral radius of, respectively the matrix  $A^U$ , and  $A^{MH}$ . The spectral radius,  $\rho^K$ , is given by the dominant root of the associated characteristic equation. So in principle, if we have two competing populations, only the one with the higher asymptotic growth factor will survive in the long run. We show in the appendix that the spectral radius of  $A^{MH}$  is larger than the spectral radius of  $A^U$ . ■

The result in Proposition 1 states that the  $MH$  architecture does strictly better than the  $U$  architecture even if the hierarchical decision architecture is not more energy efficient than the unitary process, and hence even if  $MH$  has no ex-ante evolutionary advantage over  $U$  in terms of the number of surviving offsprings,  $G_i^K$ , and survival probability,  $P_i^K$ .

The intuition behind Proposition 1 is quite straightforward. Comparing  $A^{MH}$  and  $A^U$  we can see that every entry in  $A^{MH}$  is greater than or equal to the corresponding entry in  $A^U$ . This is not surprising as every mutation reduces fitness in the  $U$  architecture, which is not the case for the  $MH$  architecture. The unitary architecture is fully connected. Hence the accumulation of mutations in any part of the decision architecture will influence the DA's overall course of action. This is not true for the modular architecture. The low level modules, for instance, are not connected to each other so a change in policy for just one of those will not affect the DA's course of action. Thus for significant fitness loss to occur, we need multiple changes in the  $MH$  architecture to take place simultaneously, an *essentially* zero probability event which can be ignored. The  $MH$  architecture thus survives under a stable environment because it is more robust to the accumulation of deleterious mutations over a DA's evolutionary dynamics.

### 3.2 Cyclically fluctuating environment

In a stable environment, through the gradual process of mutation, both unitary and hierarchical architectures will eventually stumble upon the optimal action profile  $\mathbf{a}_*$ . In this section, we consider cyclical fluctuations in the environment.

**Assumption 3-f.** *The environment fluctuates cyclically, that is, the environmental state switches from  $s$  to  $s'$  and from  $s'$  to  $s$  after every  $P \geq 1$  and  $P' \geq 1$  periods respectively, where  $\phi^U \leq d(s, s') = \phi^{MH} - \epsilon$  with  $\epsilon \downarrow 0$ . Furthermore, fluctuations are non-trivial, that is,  $G_i^K(m, s) \neq G_i^K(m, s')$  and  $P_i^K(m, s) \neq P_i^K(m, s')$  for some  $i$  and  $m$ .*

We fix the coarseness of the  $MH$  architecture at  $\phi^{MH}$  and consider the largest environmental fluctuation that can be tolerated by  $MH$  without triggering an adjustment in behavior. Essentially, we are assuming that the  $U$  architecture can adjust its action profile in response to the fluctuating environment while the  $MH$  cannot. Consistently with the complexity-efficiency trade-off (Assumption 1), we assume that continuing to execute the loss minimizing action under state  $s$  when the environmental state is  $s'$  (and vice versa) reduces offsprings and survival.

Let  $G_i^K(m, s' | s)$  denote the number of offsprings as a result of an action by a process with  $m$  harmful mutations relative to the optimal action under  $s$ , when the actual state is  $s'$ . Also, let  $P_i^K(m, s' | s)$  denote the survival probability as a result of such an action. More precisely, a modular DA executing action  $a^s$  under state  $s'$  will feature

$$G_i^{MH}(m, s' | s) = \gamma_m^G \left( \frac{1}{\phi^{MH}} \right) G_i^{MH}(m, s') \text{ and } P_i^{MH}(s' | s) = \gamma_m^P \left( \frac{1}{\phi^{MH}} \right) P_i^{MH}(m, s'),$$

where  $P_i^{MH}(m, s')$ , for instance, is the survival probability as a result of an action by a process with  $m$  harmful mutations relative to the optimum under  $s'$ . The functions  $\gamma_m^J(1/x)$  are continuous, non-increasing in  $x$  and bounded in the interval  $[0, 1]$  with  $\gamma_m^J(0) = 0$  and  $\lim_{x \downarrow d(s, s')} \gamma_m^J(1/x) = 1$  for  $J = G, P$  and  $m = 1, 2, \dots, W$ . The condition that  $\gamma_m^J(1/x)$  are non-increasing in  $x$  corresponds to the assumption that ignoring larger fluctuations in the

environment leads to proportionately larger reductions in offsprings and survival. For instance, as  $1/\phi^{MH} \rightarrow 0$ , the modular architecture will fail to adjust its behavior to arbitrarily large fluctuations in the environment, which we assume will have disastrous consequences for offsprings and survival.

Because of its greater complexity, a unitary DA suffers no reduction in fitness as a result of the environmental fluctuations, while a  $MH$  does. The unitary DA, however, consumes more energy. This is a *strict* version of the complexity-efficiency trade-off introduced in Assumption 1. In this environment it is ambiguous which of the two architectures is selected. It turns out however that we can still classify the comparative advantage of each architecture.

**Proposition 2.** *In the presence of a strict complexity-efficiency trade-off (Assumption 1), assortative mating (Assumption 2), and a cyclically fluctuating environment (Assumption 3-f), if the precision  $\frac{1}{\phi^{MH}}$  of the  $MH$  architecture is greater than a critical value, then the  $MH$  architecture has a strictly higher asymptotic population growth factor than the corresponding unitary architecture under cycles of any length or frequency and starting from any non-zero initial condition. On the other hand, if the  $MH$  architecture is sufficiently imprecise,  $\frac{1}{\phi^{MH}} \rightarrow 0$ , the conclusion is reversed and the  $U$  architecture has a higher asymptotic population growth factor.*

**Proof:** The proof is a corollary of Proposition 1. However, when the environmental state changes from  $s$  to  $s'$ , the entire matrix  $A^{MH}$  changes. With different precision levels, it may well be the case that the spectral radius of  $A^{MH}(s)$  is greater than that of  $A^U(s)$ , while the spectral radius of  $A^{MH}(s')$  is smaller than that of  $A^U(s')$ . When  $P = P' = 1$ , for instance, the asymptotic behavior of the system is determined by the spectral radii of the product matrices and we need to show that  $A^{MH}(s')A^{MH}(s)$  and  $A^{MH}(s)A^{MH}(s')$  have larger spectral radii than  $A^U(s')A^U(s)$  and  $A^U(s)A^U(s')$  respectively. See the appendix for the formal argument. ■

Intuitively, for any given loss-minimizing action profile  $\mathbf{a}_*$ , the unitary architecture is less energy efficient,  $G_i^U < G_i^{MH}$  and  $P_i^U < P_i^{MH}$ . There is thus some space for the  $MH$

architecture to be less efficient than the unitary on the precision dimension while still winning the evolutionary race. Therefore, for relatively precise  $MH$  architectures, the marginal benefit of further increasing precision by moving to a unitary architecture is outweighed by the marginal cost of increased energy consumption and increased susceptibility to the effects of mutations. For relatively imprecise  $MH$  architectures, the opposite obtains.<sup>22</sup>

### 3.2.1 Cyclical fluctuations and equilibrium heterogeneity in action profiles

Under a stable environment, the population will be dominated by DAs that minimize the loss of fitness. Evolutionary selection, therefore, will not lead to the internal conflict and heterogeneity in actual behavior we arguably observe. Hence our next step is to investigate a setup which might induce such outcomes as an evolutionary equilibrium.

Propositions 1 and 2 ignore the possibility of mutations being beneficial. In the cyclically fluctuating environment however, under our assumptions the MH architecture chooses the action which is optimal for state  $s$  even when the environmental state is  $s'$ . Beneficial mutations can in principle exist for this architecture, which will push the reference action of a module in the direction of  $a_i^{s'}$  and reduce the costs associated with the lack of precision. We expect such mutations to occur with a non-zero probability less than or equal to  $q$ .

**Assumption 4.** *Suppose for some  $i$  and  $W \geq m^* > 0$ , we have  $G_i^{MH}(m^*, s' | s) > G_i^{MH}(0, s' | s)$  and  $P_i^{MH}(m^*, s' | s) > P_i^{MH}(0, s' | s)$ , while  $G_i^{MH}(m^*, s) < G_i^{MH}(0, s)$  and  $P_i^{MH}(m^*, s) < P_i^{MH}(0, s)$ .*

The fitness of a DA will then depend on the distribution of mutations over its modules.

**Proposition 3.** *In the presence of a strict complexity-efficiency trade-off (Assumption*

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<sup>22</sup>Proposition 2 suggests that modular decision architectures should be observed later in evolutionary history, assuming encephalization increases with time. Empirically, this conjecture is in line with studies in evolutionary biology. For example the cortex, which in humans is posited to contain decision processes in addition to those of the reptilian brain, appears later in evolutionary history (in mammals) and matures later in life, particularly in humans. The distinction need not be primarily structural, however, but may instead be functional. Rats and humans for instance have the same mammalian brain structures. Despite this structural similarity, Proposition 2 implies that rats should behave more in line with the unitary model since they are much less encephalized than humans. And indeed, laboratory experiments, (Gardner and David 1999, Berridge 1999), show support for this hypothesis.

1), assortative mating (Assumption 2), in a cyclically fluctuating environment (Assumption 3-f), and in the presence of beneficial mutations (Assumption 4), evolutionary selection induces (i) a non-trivial fraction of the population with decision modules that have conflicting models of optimal behavior and (ii) a non-trivial number of DAs that choose actions which are suboptimal with respect to the current environmental state.

**Proof:** Clearly now the relative number of DAs with executive processes with  $m^*$  mutations relative to the optimum under state  $s$  will grow when the environment switches to  $s'$ . On the other hand, when the environment switches back to  $s$ , the relative number of DAs with executive processes that take the optimal action under  $s$  will grow. Thus as long as the environment continues to fluctuate, no single type will completely dominate the asymptotic population distribution of MHAs. ■

The intuition behind Proposition 3 is that when precision is imperfect, conflict among the reference policies of modules has a positive value from an evolutionary standpoint. This is because a redundant, correctly specified model for the current state becomes a rigid, misspecified model in the event of an undetected environmental perturbation. We illustrate the importance of such internal conflicts with the following simple example.

**Numerical example** Consider a modular DA with precision  $1/\phi$  whose reproductive life lasts one period. We start in environmental state  $s$  but after every generation, the state switches between  $s$  and  $s'$  where  $d(s, s') < \phi$ . Let  $a^s$  denote the optimal action in environment  $s$  and suppose a DA can carry on at most 4 deleterious mutations relative to  $a^s$ . A DA with 5 mutations leaves no offspring in either state of nature<sup>23</sup>. Assume that a mutation or its reversal happen with probability  $q = r = 0.0001$  per generation. The set of possible actions is given by  $\{a^s, a^1, a^2, a^3\}$ , where we have ordered the sequence by the number of deleterious mutations relative to  $a^s$ —0, 1, 2, and 3 respectively—that occur in the executive process which is in charge of behavior.

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<sup>23</sup>All of the the assumptions in the example are made for tractability, since the complexity of the problem increases very quickly with  $n$  and  $W$ .

Assume that: (i)  $w(a^I, a^{s'}) < w(a^I, a^s) < w(a^I, a^3) < w(a^s, a^3)$ ; (ii)  $G(m, s) = \xi^m g$ , while  $G(m, s' | s) = \xi^{2-m} g$  for  $m = 0, 1, 2$  with  $\xi = 0.98$  and  $g = 1.03$ . Condition (i) insures that  $a^3$  will never be executed and a supervisor with reference action  $a^I$  or  $a^{s'}$  will assign control to an executive process with a reference action of  $a^I$  or  $a^{s'}$  rather than  $a^s$ . Condition (ii) suggest that mutations initially push the action in the direction of  $a^{s'}$ , which is the optimal action under  $s'$ . One push results in the action  $a^I$  which has values for offspring of  $G^{a^I}(s) = G^{a^I}(s') = \xi g$ . Two pushes are sufficient to change the action from  $a^s$  to  $a^{s'}$  and vice versa. Hence in a modular DA, two pushes require at least four mutations, two at any two of the three modules.

We have the following law of motion, where the unit of account  $c$  is a cycle that lasts two generations,

$$\mathbf{N}_{c+1} = [A(s')A(s)]\mathbf{N}_c.$$

The population structure vector is of dimension 13 since we have to take into account how the distribution of mutations across the modules of a given type of DA influences its current action and the transition probabilities to other types. Similarly, the projection matrices are  $13 \times 13$ . A more detailed description of the setup and results can be found in the appendix.

It is well known (e.g., Seneta (1981), Theorem 1.2) that the asymptotic distribution of the population for a projection matrix  $A$  is given by the positive, normalized left eigenvector  $u$  associated with the spectral radius  $\rho(A)$ , that is  $u'A = \rho(A)u'$  with  $\sum_{i=1}^{13} u_i = 1$ . Figure 2 shows the asymptotic distribution of the population over the possible actions  $\{a^s, a^I, a^{s'}\}$  under three scenarios: (i) a stable environment at  $s$ , (ii) a stable environment at  $s'$ , and (iii) a generational cycle between  $s$  and  $s'$ . As expected, under scenarios (i) and (ii), the asymptotic distribution is totally dominated by types that select the optimal course of action for the stable environment. Even though there is heterogeneity in reference policies among modules for a large fraction of the population, that conflict does not translate into behavioral heterogeneity.

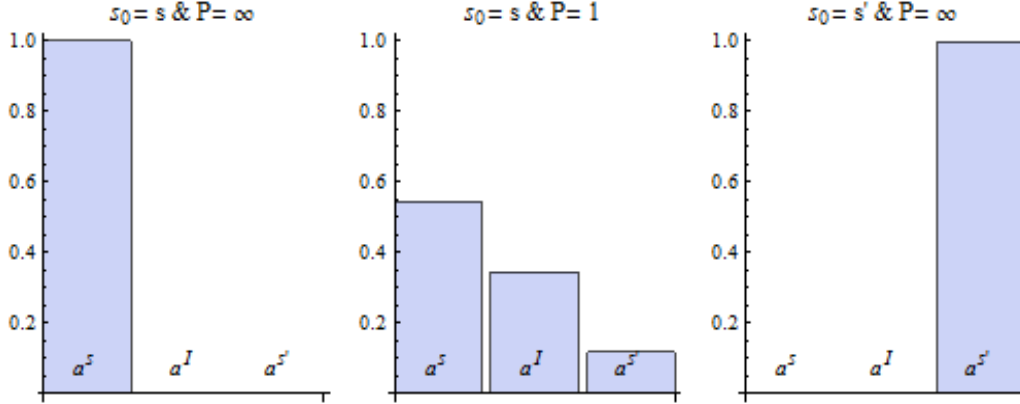


Figure 2: *Asymptotic distribution of the population over the possible actions  $\{a^s, a^I, a^{s'}\}$  under three environments.*

Under a fluctuating environment, on the other hand, we have heterogeneity in both reference models and actual behavior.<sup>24</sup> In every generation, between 45 and 90 percent of the population choose a suboptimal course of action. Even more interestingly, there are DAs—such as the type with three total mutations distributed across two modules—which possess the correct policies for each state, yet the internal conflict leads to the suboptimal course of action  $a^I$  being chosen under both  $s$  and  $s'$ . Intuitively, under imperfect precision and fluctuating environment, it pays for the population to diversify by having types which face internal conflict or exhibit suboptimal behavior. This is because it will be easier for the population to respond to the fluctuations—the types with internal conflict or suboptimal behavior will either already be behaving optimally or will require fewer mutations to start doing so when the state changes.

<sup>24</sup>The distribution is asymmetric because of our assumption that a DP can carry on at most 4 mutations. In order to have an architecture with a completely redundant reference policy  $a^{s'}$  we require 6 mutations, which is ruled out a priori. Hence our example is inherently biased against the presence of types that execute the action  $a^{s'}$ .

## 4 Hierarchical decision processes in economics

Our results provide an evolutionary justification for the models of *multiple selves* recently explored by economists. For instance, our result (Proposition 3) that evolutionary selection would favor hierarchical modules characterized by conflicting models of optimal behavior, and even by choices which are suboptimal with respect to the current environmental state, could explain the "puzzles" observed in laboratory and field studies of intertemporal choice in self-control environments. Frederick, Loewenstein, and O'Donoghue (2002) comprehensively survey this evidence. To illustrate this point, we translate into our framework the first multiple selves model, developed by Thaler and Shefrin (1981), that studies self-control and attempts to explain these intertemporal choice "puzzles".<sup>25</sup>

This model is formulated in terms of the strategic interaction between two "actors", a farsighted "planner" and a myopic "doer". The two actors are explicitly interconnected in the sense that actions by one agent directly influence the objectives of the other. In this sense, it does not immediately appear that a modular hierarchical decision architecture could represent an individual decision maker in Thaler and Shefrin. It turns out however that when the objective functions are properly defined, the policy function of a given *MH* architecture corresponds to a discrete choice approximation of the policy function of their model.

In Thaler and Shefrin's model, the farsighted planner and the myopic doer are distinct in the utility functions with which they evaluate consumption plans. Specifically, the doer cares only about current consumption, which is represented by some concave utility function  $Z_t(c_t, \theta_t)$ , with  $Z_t(c_t, 0)$  strictly increasing, and where  $\theta_t \geq 0$  is a parameter which influences the value of  $c_t$  at which  $Z_t$  reaches a maximum. The planner, on the other hand, cares about lifetime utility represented by some strictly increasing function  $V(Z_1, Z_2, \dots, Z_T)$ .

Given that the preferences of the two actors differ, there will typically be a conflict between them. Thaler and Shefrin assume that the planner can modify the doer's behavior at time  $t$  by adjusting the preference parameter  $\theta_t$ . The value of  $\theta_t$  thus represents the

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<sup>25</sup>See also Fudenberg and Levine (2006) and Loewenstein and O'Donoghue (2007) for recent extensions.

modification the planner exerts on the doer at time  $t$ , where  $\theta_t = 0$  means no modification. Influencing the doer is costly, however, in the sense that  $\partial Z_t / \partial \theta_t < 0$ . In addition, it is assumed that  $d\theta_t / dc_t(Z_t = Z) < 0$ : the lower the desired value of  $c_t$ , the bigger the modification and hence the cost that is required to adjust behavior.

Let  $c_t(\theta_t)$  denote the policy of a doer with utility function  $Z_t(c_t, \theta_t)$ . Given a lifetime income stream with present value  $y$ , an individual consisting of a planner and a doer will behave as if solving

$$\begin{aligned} & \max_{(\theta_1, \dots, \theta_T) \geq \mathbf{0}} V(Z_1(c_1(\theta_1), \theta_1), \dots, Z_T(c_T(\theta_T), \theta_T)) \\ & \text{s.t.} \quad \sum_t c_t(\theta_t) \leq y. \end{aligned}$$

We now map a two-period version of this model into our setup and show that the modular hierarchy considered in our paper provides a discrete choice approximation to the above framework. Consider an individual with endowment  $y$  who lives for two periods, that is, who has to choose how to allocate consumption between two periods. Suppose the individual behaves according to a modular hierarchical decision process in which each of the two level 1 modules are defined by the vector  $(\theta_i, 0)$ , for  $i = 1, 1'$ .<sup>26</sup> That is, for each executive module, the objective  $Z(c, 0)$  is strictly increasing in consumption in the second (last) period in life. Module  $i$  then recommends consumption for period 1 given by

$$c(\theta_i) = \arg \max_{c \in [0, y]} Z(c, \theta_i).$$

On the other hand, the reference policy of the level 2 module (the controller), is given by

$$c_2 = \arg \max_{c(\theta) \in [0, y]} V[Z(c(\theta), \theta), Z(y - c(\theta), 0)],$$

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<sup>26</sup>A natural interpretation of this formulation of the level 1 modules is that they represent different self-control levels.

where  $c(\theta)$  is the policy associated with the objective  $Z(c, \theta)$ . Then the DM will behave according to  $c^*$  given by

$$c^* = \arg \max_{c \in \{c(\theta_1), c(\theta_{1'})\}} - [c - c_2]^2.$$

Note that if the parameter space in Thaler and Shefrin (1981) is reduced to the set  $\{0, \theta_1, \theta_{1'}\}$ , the policy of the *MH* architecture described above will correspond exactly to the optimal policy of the decision maker in their model. Hence the *MH* architecture produces a discrete choice approximation to the behavior described by Thaler and Shefrin’s self-control model.

Recently, Bernheim and Rangel (2004) and Benhabib and Bisin (2005) have developed models of multiple decision processes that have more explicit neuroscientific basis. They fit into the *MH* architecture exactly rather than as approximations. The crucial difference is that in these models there are multiple level 1 modules with independent objectives. Each level 1 module recommends a course of action and control is allocated to one of the modules based on the particular circumstances. This last step corresponds precisely to the level 2 of a *MH* architecture where one of the policies recommended by the first stage modules is executed. A detailed *MH* description for each of these models is available from the authors upon request.

## 5 Conclusion

We have shown that modular hierarchical architectures of decision processes can be evolutionary selected. This is because a *MH* architecture saves energy while providing robustness against the effects of harmful mutations. In addition, we have shown that under a cyclically fluctuating environment, conflict among decision modules appears to have a positive evolutionary value, as it is a source of diversification against the influences of undetectable fluctuations in the environment.

It should be noted that we have analyzed only one potential benefit of modular hierarchical architectures. In fact,  $MH$  architectures may confer many other benefits to the decision makers that possess them. Some promising directions include the possibility for greater adaptability in response to observable changes in the environment, the ability to process information in parallel fashion, and the ability for certain modules to specialize in the analysis and execution of certain behaviors. We believe exploring any of these will improve our understanding of decision processes and the behavior of decision makers who possess them.

## 6 Appendix

### Proof of Proposition 1:

In the general case with  $n$  age groups and  $W$  maximum total mutations, the population structure vector will enumerate (i) all types with different total mutation loads and (ii) for a given total number of mutations, all possible distributions of mutations across the nodes in the given decision architecture. We can then compare the two projection matrices  $A^U$  and  $A^{MH}$  entry by entry. Consider the matrix row associated with type  $N_i^{j,k,l}$ , where we have  $M = j + k + l \leq W$  and  $i \leq n$ . Each element in that row will be a product of the transition probability between the two particular types and the value for the number of surviving offspring or the survival probability of type  $N_i^{j,k,l}$ . The transition probabilities are the same in both matrices since the mutation process is exactly the same in both decision architectures.

Now consider the values for surviving offspring and survival probability for type  $N_i^{j,k,l}$ . For the unitary architecture, regardless of the distribution of mutations across the circuit, all mutations affect the executive process. Hence we have  $m^U(M) = M$ . On the other hand, in the MH architecture, we know that  $m^{MH}(M) \leq \max\{j, k, l\}$ , where the inequality is strict if  $\max\{j, k, l\} = M$ . Specifically, the equality will hold in the situation where  $\max\{j, k, l\} < M$ ,  $\max\{j, k, l\}$  mutations occur in an executive module, and the number of

mutations in the controlling module brings its reference policy closer to the action associated with  $\max\{j, k, l\}$  mutations than to the reference action of the other executive module. We thus have  $G_i(m^{MH}(M)) > G_i(m^U(M))$  and  $P_i(m^{MH}(M)) > P_i(m^U(M))$ . But then, the projection matrix  $A^{MH}$  can be obtained from  $A^U$  by increasing each of its entries by either 0 or some positive amount. But since  $A^U$  is a nonnegative irreducible matrix, the Perron-Frobenius theorem [see for instance Thm 2.7. in Varga (2000)] implies that we must have  $\rho^{MH} > \rho^U$ . ■

### Proof of Proposition 2:

Consider the threshold value  $\phi^*$  defined by

$$\phi^* = \arg \max_{x \geq d(s, s')} \{x\}$$

$$\begin{aligned} \text{s.t. } \quad \gamma_m^G(1/x)G_i^{MH}(m, s') &\geq G_i^U(m, s') & \forall(i, m), \\ \gamma_m^P(1/x)P_i^{MH}(m, s') &\geq P_i^U(m, s') & \forall(i, m). \end{aligned}$$

Clearly, given that  $\lim_{x \downarrow d(s, s')} \gamma_m^J(1/x) = 1$  and  $\gamma_m^J(0) = 0$ , a solution to the above program will always exist. Moreover, given that  $G_i^{MH}(m, s') > G_i^U(m, s')$  and  $P_i^{MH}(m, s') > P_i^U(m, s')$ , we know that  $\phi^* > d(s, s')$ . But then for a MH architecture of coarseness  $\phi^{MH} \in [d(s, s'), \phi^*)$ ,

$$G_i^{MH}(m, s' | s) > \gamma_m^G(1/\phi^*)G_i^{MH}(m, s') \geq G_i^U(m, s')$$

and

$$P_i^{MH}(m, s' | s) > \gamma_m^P(1/\phi^*)P_i^{MH}(m, s') \geq P_i^U(m, s').$$

The above inequalities say that for precision levels of the modular architecture above  $1/\phi^*$ ,

the benefit of increasing precision further by going to a unitary architecture is outweighed by the increased energy consumption and mutation vulnerability of that architecture.

So suppose we start in environment  $s$ . Following the reasoning of Proposition 1, we know that  $A^{MH}(s)$  is an increasing transformation of  $A^U(s)$  and hence  $\rho^{MH}(s) > \rho^U(s)$ . Now suppose the environment changes permanently to  $s'$ . The above inequalities imply that  $A^{MH}(s')$  is again an increasing transformation of  $A^U(s')$  which implies  $\rho^{MH}(s') > \rho^U(s')$ . Note that when the environmental state changes, the unitary DA switches to the newly optimal profile. On the other hand, the modular DA continues to operate according to the old profile. Even though the modular DA behaves suboptimally, for  $\phi$  small, its superior energy efficiency and mutation resistance allow it to outperform the unitary DA even under the new environment.

Under short cycles,  $P = P' = 1$ , the asymptotic behavior of the system will be determined by the spectral radii of the products  $A(s')A(s)$  and  $A(s)A(s')$ . To see this, note that starting in environment  $s$ , after  $c$  such cycles we will have

$$\mathbf{N}_c = [A(s')A(s)]\mathbf{N}_{c-1},$$

where the unit of account  $c$  is now a cycle lasting two periods. But we know that  $A^{MH}(s)$  and  $A^{MH}(s')$  are increasing transformations of  $A^U(s)$  and  $A^U(s')$ . And since all of these matrices are nonnegative, the products  $A^{MH}(s)A^{MH}(s')$  and  $A^{MH}(s')A^{MH}(s)$  must be increasing transformations of  $A^U(s)A^U(s')$  and  $A^U(s')A^U(s)$ . This is because each element of the product matrices is a dot product of two nonnegative vectors. For instance, let  $A_{ij}^K(s, s')$  be the (row  $i$ )-(column  $j$ ) element of  $A^K(s)A^K(s')$ . Clearly,  $A_{ij}^K(s, s') = \sum_j A_{ij}^K(s)A_{ji}^K(s')$ . But since  $A_{ij}^{MH}(s) \geq A_{ij}^U(s)$  and  $A_{ij}^{MH}(s') \geq A_{ij}^U(s')$  for any  $i$  and  $j$  and all matrices are nonnegative, we must have  $A_{ij}^{MH}(s, s') \geq A_{ij}^U(s, s')$  with the inequality strict for at least one pair  $ij$ . But then  $\rho^{MH}(s, s') > \rho^U(s, s')$  and using similar reasoning,  $\rho^{MH}(s', s) > \rho^U(s', s)$ .

For  $P > 1$  or  $P' > 1$ , the reasoning is exactly the same, except that now we have to determine the spectral radii of  $[A(s)]^P[A(s')]^{P'}$  and  $[A(s')]^{P'}[A(s)]^P$ . But since  $A^{MH}(s)$

is an increasing transformation of  $A^U(s)$ ,  $[A^{MH}(s)]^P$  will be an increasing transformation of  $[A^U(s)]^P$  and the same for state  $s'$ . But then the same result as with  $P = P' = 1$  obtains. Hence as long as MHA's precision is sufficiently high,  $1/\phi > 1/\phi^*$ , the modular DA will outperform asymptotically a unitary DA of the same size under both symmetric and asymmetric environmental cycles of any frequency.

For the final statement in the proposition, note that  $\lim_{(1/x) \rightarrow 0} \gamma_m^J(1/x) J_i^{MH}(m, s') = 0 < J_i^U(m, s')$  for  $J = G, P$ . Hence  $\lim_{(1/x) \rightarrow 0} A^{MH}(s') = \mathbf{0}$  and any unitary DA with positive precision will have a higher asymptotic growth factor under any type of cycle. ■

### Sexual Reproduction with Random Mating:

When mating is random, the projection matrix for each sex will reflect the flows across types for that particular sex. Moreover, the entries in each projection matrix will depend on the frequency distribution of types from the other sex. When agents from different types mate, only the type of one of the parents will be inherited. Hence the daughter of a particular female agent will be of the same type as her mother only with probability 1/2. Nevertheless, for any steady state  $MH$  population distribution, we can provide a sufficient condition under which all of our results hold locally around that steady state for random mating and any steady state  $U$  distribution.

**Proposition 4:** *Let  $(f_j^0)_{j=1}^q$  be a steady state vector of frequencies of  $MH$  males or reproductive age  $j$  with 0 total deleterious mutations, so that  $\sum_{j,m} f_j^m = 1$ . If  $(\sum_j f_j^0) G_i^{MH}(m, s) > G_i^U(m, s)$  for any  $i, m$ , and  $s$ , Propositions 1, 2, and 3 hold locally around this steady state.*

**Proof:** To see why the above condition is sufficient, note that the survival probabilities do not depend on the mating process so nothing changes as far as the rows of the projection matrices determined by  $P_i$  are concerned. On the other hand, the expected number of offsprings of each type does depend on the mating process. The best case scenario for the  $U$  population is when in a steady state it is dominated by males with 0 deleterious mutations. In that case any off-diagonal entry in the first row of the female projection matrix will have a positive entry. In particular, 1/2 of the daughters produced by a mother

of a given type will have the type  $(0, 0, 0)$  of their father. On the other hand, for the  $MH$  population that will be true only for  $(1/2) \cdot (\sum_j f_j^0) < 1/2$  of the daughters. Hence as long as  $(\sum_j f_j^0)G_i^{MH}(m, s) > G_i^U(m, s)$ , any entry in the first row of  $A^{MH}$  will be greater than the corresponding entry in  $A^U$ . Moreover, since the  $U$  population is dominated by males of type  $(0, 0, 0)$  while the  $MH$  population is not, the entries for any other row in  $A^{MH}$  will be greater than or equal to the corresponding entries in  $A^U$  since there will be no flows, except for mutations, across other types in the  $U$  population. But then  $A^{MH}$  is a nondecreasing transformation of  $A^U$ . We thus must have  $\rho^{MH} > \rho^U$  and all of our previous conclusions carry through. ■

### Numerical Example:

Under the specified assumptions, we have to distinguish among 13 types of DAs: (1) no mutations, (2) one mutation, (3) two mutations in the same module, (4) two mutations in different modules, (5) three mutations in the same module, (6) three mutations in two modules with either zero or two mutations in the controller, (7) three mutations in two modules with one mutation in the controller, (8) three mutations in three modules, (9) four mutations in the same module, (10) four mutations occurring two by two, (11) four mutations occurring three by one with either zero or three mutations in the controller, (12) four mutations occurring three by one with one mutation in the controller, and (13) four mutations in three modules. The types differ according to the action that they execute and the probability with which they transition to other types. Specifically, types 1, 2, 3, 5, 9, and 12 always execute action  $a^s$ , types 4, 6, 8, 11, and 13 always execute action  $a^I$ , and types 7 and 10 always execute action  $a^{s'}$ .

The projection matrices  $A(s)$  and  $A(s')$  are simple but tedious to represent fully. Since the population structure vector  $\mathbf{N}_t$  is of dimension 13, the projection matrices  $A(s)$  and  $A(s')$  are  $13 \times 13$ . To illustrate, the 3rd rows of  $A(s)$  and  $A(s')$  represent the inflow of DAs into a DA with two mutations in the same module. Specifically, we have

$$A_3(s) = \begin{bmatrix} 0 & rg/3 & (1-2r)g & 0 & rg & rg/3 & rg/3 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

and

$$A_3(s) = \begin{bmatrix} 0 & rg\xi^2/3 & (1-2r)\xi^2g & 0 & rg\xi^2 & rg\xi^2/3 & rg\xi^2/3 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

where we have assumed that mutations are independent, occur with the same probability, and occur in each module with probability  $1/3$ .

The asymptotic distribution for a stable environment at  $s$  turns out to be given by

$$u(s)^T = \begin{bmatrix} 0.367 & 0.252 & 0.173 & 0.001 & 0.119 & 0 & 0 & 0 & 0.07 & 0 & 0 & 0.018 & 0 \end{bmatrix},$$

where the row may not sum to 1 due to rounding off. The population is clearly dominated by DAs executing action  $a^s$  with only 0.001 of the DAs behaving according to  $a^I$ . Even though there is conflict among modules for over 70 percent of the population, that conflict does not translate into behavioral heterogeneity.

If the environmental state changes permanently to  $s'$ , we have

$$u(s')^T = \begin{bmatrix} 0 & 0 & 0 & 0.001 & 0 & 0.001 & 0.413 & 0 & 0 & 0.583 & 0.001 & 0.001 & 0 \end{bmatrix}.$$

Naturally, the population now is completely dominated by DA types which choose the optimal action  $a^{s'}$ . Again, there is no heterogeneity in behavior. Finally, under generational cycles between  $s$  and  $s'$ , we have the projection matrix  $A(s')A(s)$  with associated left eigenvector,

$$u(s', s)^T = \begin{bmatrix} 0.143 & 0.131 & 0.109 & 0.108 & 0.078 & 0.077 & 0.076 \\ 0.077 & 0.041 & 0.04 & 0.04 & 0.041 & 0.04 & \end{bmatrix}$$

which clearly demonstrates heterogeneity in both reference models and behavior.

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