**Evolutionary Biology: Contemporary and historical reflections upon core theory**

**Chapter 15: Genetic Evolvability: Using a Restricted Pluralism to Tidy Up the Evolvability Concept**

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**Abstract:** Advances in the empirical sectors of biology are beginning to reveal evolvability as a major evolutionary process. Yet evolvability’s theoretical role is still intensely debated. Since its inception nearly thirty years ago, the evolvability research front has put a strong emphasis on the non-genetic mechanisms that influence the short-term evolvability of individuals within populations by causing phenotypic heterogeneity, such as developmental trait plasticity, phenotypic plasticity, modularity, the G-P map, robustness, and/or epigenetic variation. However, genetic evolvability mechanisms such as mutation or recombination have a deeper history in evolutionary thought that is often overlooked by those in the evolvability research front, with recent evidence suggesting that species switch to genetic evolvability mechanisms when short-term evolvability strategies fail to relieve selective pressures. For this reason, a causal distinction must be made between genetic evolvability and the more recently emphasized *non-genetic (or evo-devo) evolvability* to allow for its maturation as a central explanatory concept. I conclude by arguing that the anachronisms of the scientific process are the main culprit behind recent divisions in biology and likely beyond. To streamline theoretical progress, we need to build a new science with new underlying philosophies like *restricted pluralism*.

**Genetic Evolvability: Using a *Restricted Pluralism* to Tidy Up the Evolvability Concept**

Evolvability is an unusual concept. Its *unusualness* stems from its *long past but short history* in evolutionary thought, despite its unambiguous role in the evolutionary process. Darwin assumed that all extant species hold some capacity for evolution, going so far as to suggest that some species may be better at evolving than others (Sansom, 2008). In the synthetic era (*circa* 1916-1950), theorists formalized the latter notion that species vary in their response to natural selection dependent on the production and conservation of *genetic variation* (e.g., Fisher’s [1930] *Fundamental Theorem*; Dobzhansky, 1937), therefore establishing the conceptual foundations of *genetic evolvability*.

Yet for a variety of reasons, evolvability was initially “taken for granted” and built within evolutionary theory as “a given premise” (Hansen, 2016, 83). For one, the causal mechanisms behind the production and conservation of novel genetic variation—i.e., from mutation or recombination—were assumed to be the result of “random” or stochastic processes separate from selective influence[[1]](#footnote-1). A causal boundary was drawn between (1) *the random or stochastic mechanisms that produce heritable variation* and (2) *the process of natural selection acting on this variation to cause adaptation* (Mayr, 1982). These became independent and sequential causal events in the adaptation process, implying that most species were continuously replenished with sufficient variation for natural selection to subsequently act upon “without any need for special mechanisms generating new variability” (Charlesworth *et al.*, 2017, 8).

However, the assumption that the production of novel genetic variation is *random* and independent of selection has been subtly overturned in the last 60 years, despite the curious reluctance of some theorists to accept these novel findings. New evidence arising from microbiology, ecology, and experimental biology has established that mutation and/or recombination modifier genes are not only *exposed to the direct influence of selection* (Otto, 2013), but most species exhibit greater flexibility to cause adaptive genetic changes in response to selective pressures than previously supposed (Swings et al., 2017; Fitzgerald & Rosenberg, 2019; Bonnet et al., 2022), often with no observable benefit to individual organisms.

This leads us to the main reason why evolvability was initially overlooked. Evolvability is an emergent dispositional property whose manifestation is causally relevant at higher levels of biological organization over longer stretches of time and frequent spatial changes—with several biologists viewing evolvability as *the best example* of an emergent biological adaptation (Lloyd & Gould, 1993; Maynard-Smith, 1998; Folse III & Roughgarden, 2010). Yet empirical limitations and methodological constraints have naturally obscured the causal complexity of biological systems for the majority of evolutionary research. Early genetics research was often limited to within-population analyses (Nei, 2013) and performed within restrictive spatiotemporal parameters (Ford, 1964; Levins, 1968; Endler, 1986), therefore concealing the complex evolutionary and selective dynamics of natural populations. As a result, evolutionary theory was initially constructed in an abstract vacuum that was not particularly representative of evolution in nature (Otto, 2009; Hendry, 2017).

The divisions between theory and empiricism were further exacerbated within the 20th-century scientific zeitgeist of *logical positivism,* which favored the mathematical reductionism of theoretical population genetics (Smocovitis, 1996). Evolvability was therefore *imperceptible* or largely ignored by evolutionary theorists who placed a premium on reducing biological causation to one privileged level or lower levels of biological organization. Biologists clinging to these theoretical traditions still doubt the empirical realism and/or theoretical significance of evolvability for precisely the same reasons (e.g., Barton & Partridge, 2000; Partridge & Barton, 2000; Chicurel, 2001; Poole *et al.*, 2003[[2]](#footnote-2); Sniegowski & Murphy, 2006; Lynch, 2007; Charlesworth *et al.*, 2017).

Yet now in the age of evolutionary ecology where we can readily observe how evolutionary and selective dynamics unfold in the space and time of capricious ecosystems, and/or construct real-world experimental parameters that simulate these natural contexts, evolvability is beginning to be revealed as a major evolutionary process. Evolvability explanations are essential to explain why some species survive when others go extinct within *the evolutionary rescue* research front (Gomulkiewicz & Holt, 1995; Carlson *et al.*, 2014; Bell, 2017). A clear causal link has also been established between genetic evolvability mechanisms and the evolutionary survival of species or lineages—e.g., from **meiotic recombination** (Bell, [1982] 2019), **stress-induced mutagenesis** (Ram & Hadany, 2012; 2014; 2019), **hypermutation** (Swings et al., 2017), **horizontal gene transfer** (Soucy et al., 2015), **transposable element domestication** (Brunet & Doolittle, 2015), and **gene duplications**/**whole-genome duplication events** (Van de Peer et al., 2017). The observed ubiquity and conservation of these genetic evolvability mechanisms across biological domains point to higher-level selective processes such as *species or lineage selection* as the underlying causal reasons why these mechanisms are maintained in the long-term, thereby facilitating adaptive evolution through the production, conservation, or domestication of novel genetic variation when environments change, often with no observable benefits to individual organisms or *selfish genes*.

Thus, the *unusualness* of evolvability in the history of evolutionary thought is precisely what makes it an interesting concept. The reasons why a central process such as evolvability can go relatively unnoticed in theory shed specific light on the philosophical anachronisms that have been stalling theoretical progress for over a century. Today, philosophers of biology generally agree that complex biological phenomena such as evolvability—which are only just being revealed by superior empirical methodologies—justify a switch in theoretical tactics away from explanatory reductionism, monism, and monocausal modeling towards a theory that embraces pluralistic, multilevel, and multicausal explanations (Dupre, 1993; Mitchell, 2003; 2009; Potochnik, 2017; Anjum & Mumford, 2018).

However, the ensuing chapter has little to do with *the realism of evolvability* or what can be accomplished by integrating evolvability into modern evolutionary theory. For those evolutionary biologists who derive from empirically rich traditions, the central role of evolvability in the evolutionary process is self-evident. Yet I also take issue with how evolvability is presented by progressives on the other side of the spectrum, which will be the focus of this chapter.

Evolvability has been referred to as “a cornerstone of the EES” (Pigliucci, 2008, 75; Pigliucci & Muller, 2010) because (i.) development was ostensibly missing from the modern synthesis, and (ii.) evolvability is largely construed as a developmental phenomenon by most in the evolvability research front (Ibid; Hanson, 2016; Hansen *et al.*, *forthcoming*; Nuno de la Rosa, 2017). However, the historicity of (i.) is in question (see for more chapter 12; Futuyma, 2017), and here I reject (ii.) that evolvability is largely a developmental phenomenon. Evolvability may very well be “the proper focus of evo-devo” (Hendritske *et al.*, 2007), but *evo-devo is not the proper focus of evolvability*. Genetic evolvability has always been, and shall remain, the central focus of evolvability thought.

Hansen *et al*. (*forthcoming*) continue in the tradition of placing a strong emphasis on development and broadly argue for *an unrestrictive or “anything goes” type of pluralism* for the evolvability concept, following similar philosophical prescriptions by Nuno de la Rosa (2017), Brown (2014), and Pigliucci (2008). But a budding concept such as evolvability does not benefit from an overly broad type of *pluralism, explanatory or methodological*. New concepts benefit from a *restricted pluralism*, where we can still accept the many different viewpoints of evolvability, but leave space for further conceptual refinements and causal distinctions made between these (oftentimes competing) viewpoints.

Here I suggest the utility of maintaining the ultimate/proximate causal distinction (i.e., *Weismann’s barrier*) of modern genetic theory to build a more accurate causal picture of adaptation by *evolvability* (c.f. Uller & Laland, 2019; Laland *et al.*, 2011). *Why?* Because drawing a causal distinction between *genetic evolvability* and the more recently emphasized *non-genetic* (or *evo-devo*) *evolvability* grants us taxonomic clarity[[3]](#footnote-3). It organizes similar phenomena while also maintaining a concreteness in conceptual parameters that should be preferable to broad conceptualizations of evolvability that categorize all evolvability-related explanandum under the same conceptual umbrella—*i.e.*, phenotypic plasticity, developmental plasticity, epigenetic variation, the genotype-phenotype map, modularity, robustness, evolutionary capacitance, and adaptive genetic variation. Re-organizing the evolvability concept by making further causal refinements is thus a must if evolvability is to progress into a mature concept within the background of modern evolutionary theory.

**The Neglected *Long Past* of Genetic Evolvability**

“Concepts such as evolvability, for instance, did not exist in the literature before the early 1990s… [T]he majority of the new work concerns problems of evolution that had been sidelined in the (*Modern Synthesis*) and are now coming to the fore ever more strongly, such as the specific mechanisms responsible for major changes of organismal form” (Pigliucci & Muller, 2010, 4 & 12).

But evolvability was never “sidelined”, at least in the same way as the other proposed novel concepts of the *EES*, nor was it non-existent in the literature before the 1990s. Early theorists and empiricists—such as Weismann, Fisher, Ford, Wright, and Dobzhansky—granted evolvability a central role in their investigations when they were attempting to model how populations respond to selection. However, given the limitations imposed by the methods and instruments contemporary to their time, they were never able to effectively reveal evolvability dynamics, so they instead built the evolvability concept implicitly within their theoretical models (e.g., Fisher’s *Fundamental Theorem* or Wright’s *Shifting Balance Theory*). We also need to take into account the broader scientific zeitgeist, i.e. *logical positivism*,that favored reductionistic interpretations of biological phenomena (Smocovitis, 1996), thus concealing the emergent nature of evolvability.

This is why evolvability can be said to have *a short history but a long past*. Many recent historiographies on evolvability have suffered from historical revisionism and presentism by neglecting its *long past*. These historiographies—often briefly mentioned at the start of reviews—are subjectively directed towards the authors’ *present* conceptualization of evolvability. For example, the quantitative geneticist Thomas Hanson (2016) gave a brief historical account of evolvability, but only as it is conceived in developmental biology today, claiming that evolvability is a relative newcomer to evolutionary biology because development was “black-boxed” during the modern synthesis (cf. Futuyma, 2017; Chapter 12). He goes on to note that this all began to change in the 1970s and 1980s due to the renewed interest in evolutionary constraints, setting the stage for evolvability to become an official research front. Hansen & Pelabon (2021), Porto (2021), Minelli (2017), and Brigandt (2015) made similar historical assertions, seeing evolvability as a relative newcomer because of their evo-devo lens.

The issue with these historical accounts is that they fall under the fallacy of *presentism*. They regard evolvability and its history as it is most commonly presented today, as a developmental phenomenon within the context of modern biology. They entirely disregard the intellectual contexts that incubated evolvability, thus excluding a significant portion of the history of evolvability thought.

This is a misuse of history because it falsely promotes certain conceptualizations of evolvability over others. Today, this has manifested into the precedence given to an evo-devo approach of evolvability over its *long past as genetic evolvability*. How scientific ideas are conceptually constructed influences their perceived history, yet good history and science rely on the opposite to be true. *History should influence how scientific ideas are conceptually constructed*. Thus, we need an accurate philosophical history of evolvability to help inform its conceptual construction today.

Evolvability *as an idea* has a much deeper history that is indeed quite relevant to its modern conceptual construction. The philosopher Massimo Pigliucci (2008) was the first to give an historical account of evolvability *as an idea*, no matter what the biologists back then were calling it. Surprisingly, few authors have since followed in his footsteps. Here I provide a brief historiography of evolvability *as an idea* that is not currently acknowledged by those in the evolvability research front.

Many years before the coinage of the term ‘evolvability’, the main aspects of evolvability loomed in the thoughts of early biologists when they were reasoning on the functionality of genetic variation. For example, August Weismann (1889, 272; 1904, 223) was the first to explicitly note the ontological connection between (a) the production of novel variation (from recombination), (b) variation in the ability to adapt between species, and (c) the subsequent beneficial effect this would have on a biological entity higher than the individual. This was the first instance that the mechanisms behind heritable variation were considered to hold some adaptive value.

After the neo-Darwinian era, many biologists retreated into a developmental viewpoint of evolution (an era called the “eclipse of Darwinism” [Bowler, 1983]). In this era, developmental theories of adaptation, such as Lamarckian or Orthogenetic theory, superseded natural selection theory. “Adaptability”—a progenitor term for evolvability—was gained from organismal plasticity responses that tended towards Lamarckian inheritance (e.g., Baldwin, 1896; Osborn, 1896). However, Lloyd Morgan (1896) presented an eerily modern account of the evolvability process that did not suffer from any Lamarckian connotations, in which organismal plasticity or developmental mechanisms were seen as transitory responses that allow time for genetic mechanisms to cause adaptive evolution.

*The modern synthesis* (*circa* 1916-1950) delivered a decisive blow to the developmental perspectives of evolution. In this era, the population geneticist R.A. Fisher (1930) formalized Weismann’s ideas with his *fundamental theorem of natural selection.* This theorem (in the vein of physical reductionism [Smocovitis, 1996]) mathematically demonstrated that the rate of change of mean fitness is equal to the genetic variance of a species. It follows from Fisher’s theorem that the potential of a species to respond to selective pressures is contingent on the amount of genetic variation (or more precisely, additive genetic variation), which became a crude measurement of evolvability that is still in practice today by quantitative geneticists.

Like Weismann, the evolutionary geneticist Theodosius Dobzhansky was an early empirical investigator into the origins and nature of genetic variation in natural populations. Due to his empirical work, Dobzhansky claimed that populations with increased variation would eventually outcompete populations with lower variation because of the fitness advantage it would eventually confer, despite the short-term fitness costs to individuals within a population (Borrello, 2010). “A species perfectly adapted to its environment may be destroyed by a change in the latter if no hereditary variability is available in this hour of need. Evolutionary plasticity can be purchased only at the ruthlessly dear price of continuously sacrificing some individuals to death from unfavorable mutations” (Dobzhansky, 1937, 126-127).

Evolutionary ecologists built off the observational work started by Dobzhansky in the latter half of the twentieth century. The concepts of “adaptability” or “environmental flexibility” captured the general idea of evolvability when ecologists would discuss how a population survives and adapts in multiple or changing environments, and how this was tied to populational properties of standing genetic variation (e.g., Levins, 1968; Lewontin 1974; Endler, 1986, 48).

Yet the original notion of evolvability as adaptive genetic variation would eventually become superseded by a far more general and broad view of evolvability that instead focused on the phenotypic consequences of transient “evolvability” mechanisms. This transition was likely due to the concomitant expansion of developmental evolutionary biology in the 1990s, around the same time that evolvability was becoming popularized (Nuno de la Rosa, 2017).

Therefore, the evolvability research front began to mature within an intellectual milieu that placed a greater emphasis on development and the phenotype, moving away from what many saw as the outdated reductionism of gene-centered perspective. I think the initial motivations for this movement were worthy and have inspired much progress in our thinking about evolution, as evidenced by the large compendiums now devoted to developmental thinking within evolutionary biology (e.g., Nuno de la Rosa, 2018*)*.

Evolvability is not merely a function of generating genetic variation (Burch & Chao, 2000). Explaining the evolution of complex traits requires knowledge of the organization, growth, and development of *organisms* (Kirschner & Gerhart, 2005). No sensible student of evolvability could ignore the causal importance that development plays in the adaptation process, especially when we start to distinguish the evo-devo concepts whose causal explanatory importance is likely greater (e.g., the G-P map and/or developmental modularity) than the non-genetic concepts whose evolutionary consequences are perhaps more transient or less consequential (e.g., epigenetic variation, protein promiscuity).

However, by focusing too greatly on development, those in the evolvability research front have continually overshadowed the causal explanatory import of long-term (or higher-level) genetic evolvability. Massive and pertinent literatures exist outside of the traditional bounds of evolvability research, above (e.g., ecology) and below (e.g., microbiology) the typical scope of developmental research on organisms.

Evolvability cannot be *only* couched in terms potent to evo-devo, precisely because 30 years of research have made it abundantly clear that evolutionary biologists and developmental biologists *generally* investigate phenomena that operate at different timescales, at different levels of biological organization, or that differ in their downstream evolutionary consequences. Evo-devo approaches can readily explain short-term adaptation to novel environmental stimuli, but they run into difficulties when they try to explain longer-term evolutionary trends and adaptation at higher levels. By disregarding the successes of modern genetics and genetic theory, those in the evo-devo camp have routinely overrepresented the theoretical significance of development in the evolutionary process, with evolvability being the perfect example of this trend. This is why we need to reemphasize the importance of the G side of the G-P map, to aid in the explanation of long-term or *macroevolvability* trends.

**Evolvability Theory Today: The Issue(s) with Evolvability**

Within the past thirty years, understanding why biological entities vary in their capacity or propensity for evolution—*i.e., evolvability*—has bloomed into a central research front within evolutionary biology, catching the attention of biologists from every major sub-discipline (Nuno de la Rosa, 2017; e.g., Houle, 1992; Wagner & Altenberg, 1996; Kirschner & Gerhart, 1998; Gerhart & Kirschner, 1997; 2007; Earl & Deem, 2004; Pigliucci, 2008; Brookfield, 2001; 2009; Wagner & Draghi, 2010; Arenas & Cooper, 2013; Brown, 2014; Minelli, 2017; Payne & Wagner, 2018; Porto, 2021; Riederer et al., 2022; Hansen et al., *forthcoming*). Despite the influx of new work that describes or mentions evolvability, it remains more conceptually fuzzy now than it did when it was first popularized over 30 years ago, evidenced by the diversity or “plurality” of conceptions of evolvability, or by the large volumes dedicated to explaining such diversity (e.g., Hansen et al., *forthcoming*).

We are no closer to agreeing on *what evolvability is*; that is, *what are the bearers of evolvability* (the entity possessing the capacity to evolve, e.g., traits, individuals, populations), *what biological features make up the causal basis or causally contribute to evolvability* (e.g., developmental systems, genetic systems) and how do they differ in their *causal attributes,* such as *causal influence* (Lewis, 2000) or *causal specificity* (Woodward, 2010), and finally, *what phenomena should evolvability be conceptualized to explain?*

Brookfield (2001; 2009), Love (2003), Pigliucci (2008), and Brigandt *et al.*, (*forthcoming*) mark the conceptual confusion surrounding evolvability as likely the result of the term being used to refer to multiple distinct, but overlapping, phenomena related to the production or storage of novel variation (both genetic and phenotypic) and its consequent effects on adaptation. It is for this reason that most in the evolvability research front agree on the prescription of a broad and *unrestrictive pluralism* for evolvability to solve its conceptual issues (e.g., Hansen *et al.*, *forthcoming*; Nuno de la Rosa, 2017; Brown, 2014). These broad models of evolvability encompass all evolvability-like phenomena under the same conceptual umbrella—i.e., phenotypic plasticity, developmental trait plasticity, epigenetic variation, G-P map, modularity, robustness, evolutionary capacitance, or genetic evolvability.

While it is true that the eclectic assemblage of definitions and associated concepts certainly speaks to the need for a broad-type pluralism of ‘evolvability’ or something similar across multiple domains, taking such a broad and inclusive approach exacerbates the issue(s) with evolvability. What these broad conceptions of evolvability often gain in generality (e.g., are easily understood, increased explanatory breadth) they lose in specificity (e.g., explanatory/predictive power, causal adequacy, theoretical coherency). Much of the conceptual confusion surrounding evolvability is caused by this lack of specificity, which in turn hinders the capacity of evolvability to exist within the theoretical background of modern evolutionary theory, like an oversized puzzle piece.

**Non-Genetic (or *Evo-Devo*) Evolvability**

To expand on these issues, let us consider the most popular cluster of evolvability conceptions, *the evolutionary developmental biology (evo-devo) concept of evolvability* (Nuno de la Rosa, 2017). Richard Dawkins (1989) and Peter Alberch (1991) jumpstarted the evo-devo concept of evolvability with their initial focus on development, effectively defining evolvability as a “property of embryological systems, i.e., certain types of developmental systems are better at evolving” (Alberch, 1991, 9).

With their two publications in top journals, Wagner & Altenberg (1996) and Kirschner & Gerhart (1998) propelled the evo-devo approach into the mainstream and made development the proper focus of evolvability theory (Nuno de la Rosa, 2017). The authors broadly emphasized the role that development plays in the production or structure of phenotypic variation, defining evolvability as *the capacity to generate heritable adaptive phenotypic variation* (influencing others to do the same: e.g., Payne & Wagner, 2018; Minelli, 2017; Porto, 2021). They argue that properties of developmental systems—such as the G-P map, protein versatility, weak linkage, compartmentalization or modularity, developmental trait plasticity, exploratory behavior, or the epigenome—were related to evolvability since they bias the amount and kind of phenotypic variation expressed in evolutionary systems so that more favorable and nonlethal kinds of variation are made available to natural selection in times of need.

These approaches have been referred to as *non-genetic evolvability* since they go beyond the mechanisms of genetic change, from mutation or recombination, to focus on the organizational and structural mechanisms of organisms that influence and optimize variation production in complex systems (Wagner & Laubichler, 2004). Of course, many “non-genetic” mechanisms may be underpinned by genetic processes, as rightly recognized by many in the evolvability research front. However, the organizing theme of the evo-devo concept of evolvability is the special emphasis that it places on the production or structure of phenotypic variation since “phenotypic variation is the selectable material of natural selection”[[4]](#footnote-4) (e.g., Brookfield, 2001; Payne & Wagner, 2018).

For example, significant research attention within the evolvability research front has been directed towards the modularity of the G-P map and how phenotypic robustness promotes evolvability (G. Wagner & Altenberg, 1996; Kirschner & Gerhart, 1998; A. Wagner, 2005; Masel & Trotter, 2010; Wilder & Stanley, 2015; Pavlicev, *forthcoming*). This work has convincingly shown that most species have an innate “evolvability” to (a) buffer lethal mutations and (b) reduce the number of mutations needed to produce phenotypically novel traits. Both observations correspond to the way that genetic variation is modulated (compartmentalized) and turned into phenotypic variation by the G-P map.

However, despite its success to discover new and exciting phenomena related to evolvability, the evo-devo approach has perpetuated and, in some cases, exacerbated the conceptual issues with evolvability. Several have argued that the broadness of the evo-devo concept is a virtue, thus focusing on the explanatory breadth of evolvability to capture multiple overlapping phenomena (e.g., Pigliucci, 2008; Nuno de la Rosa, 2017; Brown; 2014; Payne & Wagner, 2018; Brigandt *et al.*, *forthcoming*). Taking such a broad approach to evolvability has in turn distracted us from the complete causal field of evolvability, including upstream causal events like genetic evolvability.

**Drawing a Causal Distinction Between Non-Genetic and Genetic Evolvability**

Because of its emphasis on development and phenotypic variation, the evo-devo concept often fails to delineate between short- and long-term evolvability phenomena. This is to say that the evo-devo concept ***does not delineate*** between the mechanisms that generate genetic, long-term, and heritable change from the mechanisms that generate non-genetic and non-heritable (or *transiently* *heritable*) change, such as epigenetic variation or stochastic gene expression. Both types of mechanisms contribute to the evolvability of populations, but *they contribute in different and significant ways*. Non-genetic evolvability mechanisms generate phenotypic heterogeneity without creating genetic variation, making these changes more transient in the evolutionary process.

For example, in a recent review of evolvability published in *Nature Review Genetics*, Payne & Wagner (2018) considered four non-genetic mechanisms that create phenotypic heterogeneity as “evolvability mechanisms”—i.e., stochastic gene expression, errors in protein synthesis, epigenetic variation, and protein promiscuity[[5]](#footnote-5). According to the authors, the phenotypes created by these non-genetic mechanisms “may themselves be heritable, eventually made permanent by mutation or epigenetic modification, or they may simply ‘buy time’ for a population to adapt in other ways to an environmental change” (Payne & Wagner, 2018, p. 25)[[6]](#footnote-6).

The authors go on to demonstrate this point by arguing that epigenetic modifications can create phenotypic heterogeneity from the changes in the protein conformations of prions. For example, the prion [PSI+] in *S. cerevisiae* is an aggregated conformation of the translational suppressor Sup35 protein, which causes reduced translational fidelity. Some of these errors reveal cryptic genetic variation, producing adaptive phenotypes that are transiently heritable for several generations in response to pressures. The authors suggest that these epigenetic modifications of prions “buy time” for mutation and recombination mechanisms to catch up and cause an adaptive, long-term, heritable change.

In the causal story of evolvability extrapolated by the authors, the non-genetic mechanisms that cause phenotypic heterogeneity are the salient causal aspects that lead to the ensuing *evolvability*. The *causal emphasis* is put on the phenotypic variation generated, even though the authors confusingly recognize the secondary or “conditional” causal role that the non-genetic mechanisms play by “buying time” for mutation and/or recombination mechanisms to catch up and cause adaptive and long-term change. Alas, this is an example of how most causally conceive of the evolvability process today. Their attention is put on the biological mechanisms *downstream* from genetic evolvability mechanisms.

What is being neglected by the evolvability research front is the upstream disparity in causation, or a disparity in the mechanisms that cause genetic evolvability *between species*, rather than all species having the same capacity to produce, conserve, or domesticate genetic variation. Indeed, if every species had the same capacity for genetic evolution[[7]](#footnote-7), and most of the differences of variation existed at the organismal-developmental level, then the most salient aspect of evolvability, as well as the direct causal element of evolvability, would be non-genetic evolvability mechanisms that modulate invariable or stochastic genetic variation that subsequently turns into phenotypic heterogeneity.

However, species do not exhibit the same capacity for genetic evolution due to non-random selective reasons. Mutation and/or recombination rates are incredibly variable throughout taxa and levels of biology, often dependent on numerous causal factors, including selection (Lobkovsky et al., 2016; Swings et al., 2017). It has been widely appreciated in microbiology that natural selection *can causally intervene and influence the mechanisms of genetic variation, with some species being more genetically evolvable* since at least the 1960s (Fitzgerald & Rosenberg, 2019).

This seems to be a point that is strangely absent in most considerations of evolvability (e.g., Brown, 2014; Brigandt *et al.*, *forthcoming*). For example, Nuno de la Rosa & Villegas (2019) note that the G-P map governs how “random genetic mutation” translates into non-random, structured, and possibly adaptive phenotypic variation for characters exhibited by particular types of organismal systems. What is missing from these considerations is the fact that there is *non-random* discriminate sampling in the processes of mutation/recombination themselves, with the variation in these processes being best attributed to *between populations* because of the interlevel conflicts that typically accompany the emergent benefits (i.e., the individual-level costs of recombination or mutational load).

Such a disparity strongly suggests that higher-level natural selection acting on mutation/recombination modifiers is an upstream causal event from the generation of phenotypic heterogeneity that needs to be distinguished from other downstream causal events of evolvability, such as those pertaining to *non-genetic evolvability*. It also suggests that causal distinctions can be made between the amount of causal influence (Lewis, 2000) or specificity (Woodward, 2010)[[8]](#footnote-8) that these two types of evolvability exhibit, with early indicators suggesting that genetic evolvability is more causally influential and causally specific than non-genetic evolvability mechanisms.

When we draw parallels between other literatures with similar explanatory goals, such as the evolutionary rescue research front, we see similar observations arising. Developmental mechanisms (and dispersal methods) might be initially sufficient to relieve minor pressures and allow for population persistence. Yet when too great of pressures are applied, populations generally shift their strategies to facilitate adaptive evolution through genetic changes (Carlson et al., 2014; Merila & Hendry, 2013; Bonnet et al., 2022). Indeed, such a distinction is important to make in the evolutionary rescue research front, exhibited by the work that attempts to establish the time frames over which genetic change versus existing phenotypic plasticity will be most important for population persistence (Chevin *et al.* 2013, Kovach-Orr & Fussmann 2013; sources drawn from Hendry *et al.*, 2018).

The available evidence thus implies an ontological and causal distinction between the direct causal elements of genetic evolvability (e.g., evolvability mechanisms like HGT, stress-induced mutation, or meiotic recombination) that generate genotypic heterogeneity, and the non-genetic causes that influence how effective genetic evolvability mechanisms are at producing adaptive phenotypic changes (structural causes) or the developmental mechanisms that produce phenotypic heterogeneity and “buy time” for genetic evolvability mechanisms to cause adaptive evolution. This is because non-genetic evolvability mechanisms appear to be *conditional elements* of genetic change (i.e., structural causes), rather than the direct causal elements (or what is called a *triggering cause* in the causal literature) of evolvability[[9]](#footnote-9). Non-genetic mechanisms certainly aid in the facilitation of adaptive evolution, but their role is better cast as *conditional* rather than *causal*. Like a silencer to a pistol, conditional non-genetic mechanisms likely evolved to augment and modulate the mechanisms of genetic variation.

Other examples include the influence of the G-P map on evolvability since it promotes greater evolvability *but* *also greater robustness* (Pavlicev, *forthcoming*). The G-P map is best described as a structural cause that eases the selective constraints of genetic mechanisms, which in turn allows for the direct causation of genetic mechanisms to generate more adaptive mutations in the future (Masel & Trotter, 2010). Likewise, Brown (2014) noted that weak constraints on developmental traits afford a greater probability that traits can evolve in response to environmental demands. Such constraints only make the probability of a beneficial mutation of a trait more likely, whereas the direct causal action of evolvability is contingent on the genetic mechanisms (that are also probabilistically dependent but upstream causal events).

The causal distinctions that abound between genetic and non-genetic “evolvability” mechanisms—such as differences in causal influence and downstream effects, causal specificity, and/or spatial location—strongly suggest that we must maintain something like the ultimate/proximate causal distinction between genes/development (i.e., *Weismann’s barrier)* in the evolvability concept, contrary to what several progressives have argued (c.f. Uller & Laland, 2019; Laland *et al.*, 2011). For precisely the same reasons why we drew a distinction between development and genetics in evolutionary biology over a century ago (i.e., *Weismann’s barrier*), and why we still view the explanatory utility of Lamarckian or soft inheritance as inferior to hard-inheritance structures, are precisely the same reasons why we should draw a similar distinction between *shorter-term phenotypic evolvability from developmental mechanisms* and *longer-term higher-level genetic evolvability*.

If evolvability is to become a mature causal explanatory model, we must have a good grasp of its causal relations. When we are constructing a causal explanatory model, especially one that attempts to capture the complete causal field of a complex phenomenon such as evolvability, we must make further causal distinctions so that we can accurately and precisely model and replicate this process in the future. Maintaining such a causal distinction between non-genetic vs. genetic evolvability thus organizes similar phenomena while also achieving a concreteness in conceptual parameters, which should be preferable from the typically broad conceptual model of evolvability that hastily categorizes all the evolvability-related explanandum under one conceptual umbrella. We need to reemphasize the *evolvability gained from genetic changes* rather than the nondescript evolutionary potential gained from non-genetic, non-adaptive developmental processes.

**Prescribing a *Restrictive Pluralism* to Solve Evolvability’s Conceptual Issues**

Many argue for a broad or *unrestricted “anything goes” type of pluralism* to resolve the conceptual issues with evolvability, which is often overly inclusive of overlapping phenomena since they include developmental evolvability mechanisms alongside genetic evolvability mechanisms without drawing any major causal distinctions between the two types or other typologies (Hansen *et al.*, *forthcoming*; Nuno de la Rosa, 2017; Brown, 2014). Yet rather than taking such an inclusive approach, comparing and contrasting the various merits of competing accounts of evolvability may prove useful to enhance its conceptual clarity and allow for its successful integration into modern evolutionary theory.

This rationalist strategy has been referred to as *restricted pluralism*, more commonly recognized in the economics literature when strictly contrasted with an *anything goes type of pluralism* (Marques & Weisman, 2008), because it tolerates a heterogeneity of viewpoints within some sort of homogenous cluster, while simultaneously calling for the discrimination of the heterogeneity within such a cluster. This is to say that *restricted pluralism* allows for the comparison of competing models, ideas, or hypotheses based on any sort of demarcationist criteria, thus allowing space for the construction of more nuanced and complex theoretical models. Restricted pluralism is thus a rational reaction to an ever-increasing ontological complexity found in most sciences today. And a complex concept such as evolvability likely necessitates taking such a nuanced pluralistic approach.

*Restricted pluralism* goes hand-in-hand with the building philosophical literature on *scientific theoretical virtues,* which acts as the objective criteria to reliably sort through similar yet competing ideas. Philosophers of science have recently devoted much attention to systematizing the scientific theoretical virtues (Kuhn, 1977; Brock & Durlauf, 1998; Keas, 2017; Schindler, 2018). Indeed, this is an excitingly novel approach to theoretical argumentation in the sciences. Instead of arguing for a scientific theory (or a promising hypothesis) by demonstrating its underlying *empirical adequacy* or other strictly epistemic virtues (e.g., Popper, 1959), which is the most common practice in science today and throughout history, we can now compare and contrast the various scientific virtues—those of an epistemic, non-epistemic, or pragmatic nature—of a theoretical model within a neat and orderly standardized framework (e.g., Baedke, 2020).

Thanks to ecology and other empirically rich traditions that have allowed for the investigation of causally complex evolutionary dynamics over longer stretches of time and frequent spatial changes, *genetic evolvability* is now an epistemically virtuous concept. However, what also sets *genetic evolvability* apart from *non-genetic evolvability* is the non-epistemic virtue of *theoretical coherency* (or what Keas [2018] calls *universally coherent)*. *Theoretical coherency* is a non-epistemic virtue because it relates to how our knowledge is structured and how new knowledge can be best integrated within a prevailing scientific paradigm. When constructing a novel concept, we must pay heed to the existing theoretical structure; to how well the novel concept sits with most of our modern theoretical structure of evolution[[10]](#footnote-10). Yet the novelty of a promising concept often blinds us to thinking about how it might fit and integrate within an existing theoretical structure.

It is important to remember that scientific concepts are social constructs, subjectively framed to integrate homogenous phenomena or data under a common, normalized representational model that is externally valid. The “goalposts” of our models (or *conceptual parameters*) can always be moved following new observations and evidence. Often the more rigid the parameters of a concept are drawn, the easier it is to understand its causal workings in a specific context, which in turn generally enhances its understandability within the larger causal picture of putative theory. When concepts lose their rigidity, they become subject to *ad hoc* reasoning (Schindler, 2018), and they also tend to lose their meaning and procure confusion[[11]](#footnote-11). This is precisely what is happening in the evolvability literature today.

Genetic evolvability maintains *Weismann’s barrier* and thus keeps with the causal criteria of modern genetic theory better than its alternatives[[12]](#footnote-12). Non-genetic evolvability, in contrast, places too great of an emphasis on development and not enough emphasis on genetic evolvability. And while development clearly plays an integral role in the evolvability process, there is not enough evidence to discharge *Weismann’s barrier*. Until we find more evidence that demonstrates how developmental or non-genetic evolvability mechanisms influence the evolutionary process in the long term, *Weismann’s barrier* is here to stay.

It is thus problematic to encompass all the mechanisms of evolvability under one conceptual umbrella, without making any further distinctions. In the first place, the generality of these definitions makes it difficult for biologists to form a proper quantification of evolvability; one that can be used in theory by quantitative and population geneticists (Hansen *et al.*, 2011) or as a standard for experimental practice and comparison. These are important for the prediction of evolutionary outcomes in natural populations (Pigliucci, 2008; Palmer & Feldman, 2012). Often in the history of science, we have seen a tradeoff between the explanatory breadth (how many phenomena a concept can explain) and the predictive power of scientific theories. When too wide of an explanatory net is cast, predictive power becomes more difficult.

Yet generality of explanation (i.e., explanatory breadth, explanatory consistency) is still considered by many to be a hallmark of good science. However, the history of science indicates that as scientific disciplines grow and mature, they evolve to form more specific explanations that better explain the causal field of complex phenomena—*they often tend towards explanatory pluralism at a discipline-wide level* (Dupre, 1993; Mitchell, 2003; 2009). Yet scientists still instinctively lean towards this generality when constructing new conceptual models, which is a significant deterrent to forming better, more accurate, and more predictive causal explanatory models, especially in a discipline with a casually complex explanandum like biology. For these reasons, some sort of broad pluralism is indeed warranted at the discipline-wide level of biology. But pluralism should not be overly prescribed, which is often the case under an *unrestrictive or “anything goes” type of pluralism*.

This is why we must first reach a consensus within the evolutionary biology community as to what constitutes *evolvability* and set our sights away from any broad or unrestricted type of pluralism for the time being. Scientific concepts benefit from a restrictive pluralism while in their infantile stages, to first construct a sturdy conceptual parameter around one or a few readily observable phenomena and then build out from this foundational point. Explanatory pluralism generally follows once a concept is established and advanced, as standardized methods become further refined enough to investigate more peripheral phenomena related to the concept.

One needs to look no further than natural selection theory as the perfect example of this trend. Natural selection *was not ready to be pluralized* until the recent synthesis between evolutionary biology and ecology. We simply did not know enough about selective dynamics until we began to incorporate ecological analyses in evolutionary biology, which is why natural selection theory was initially best served by the philosophies of *explanatory monism* and/or *reductionism*. Early progenitors of evolutionary theory were therefore not doing a disservice by reducing or *monizing* natural selection to lower causal levels; rather, their *modus operandi* was aligned with the best interest of biology during their time, within their intellectual zeitgeist (i.e., logical positivism), and with their technological limitations and scarce epistemic reservoir.

For these reasons, taking a more narrowed or *restrictive pluralistic* approach is not only in the best interest of the evolvability concept given the available evidence, but also in the best interest of evolutionary theory more generally. This calls for the further refinement of the evolvability concept, cutting up its conceptual parameters to arrive at a more accurate causal picture of evolvability within the broader scope of evolutionary dynamics.

Evolvability is thus not ready to be a ‘foundational block’ of the *EES* (e.g., Pigliucci, 2008; Wagner & Draghi, 2010), especially when it is conceived as a developmental phenomenon. Progressives that make such calls are clearly lacking (a) sufficient empirical evidence to support their recommendations, and (b) the foresight necessary to neatly construct and integrate a novel concept into the existing theoretical structure—similar to what I have recognized in the rest of the EES as well.

**Theoretical Progress in Biology and the Failures of Modern Science**

Biology is unlike any other scientific discipline, hence why we need *scientific disunity* (Dupre, 1993; Cartwright et al., 1996). We have never undergone a paradigmatic revolution as described by the philosopher of science Thomas Kuhn in his famous *Structure of Scientific Revolutions* (1962). Biological theories are not *incommensurable* between competing or parent-offspring “paradigms”, as theory is generally built cumulatively and progressively. Biologists have been building upon the same theoretical core of adaptation, inheritance, and variation since the formalization of modern biology in the synthetic era (Smocovitis, 1996).

To echo what was said by D.J. Futuyma in chapter 12, new conceptual ideas or theoretical additions have been consistently uploaded into evolutionary theory through the “synthesis” with other biological subdisciplines. Population biology was added in the 1960s, microbiology in the 1970s, ecology in the 1980s, evo-devo and conservational biology in the 1990s, systems biology in the 2000s, synthetic biology in the 2010s—so on and so forth. Each synthesis has brought with it a new understanding of the evolutionary process, all revolving around the same theoretical core ideas as before (with a rotating yet refined emphasis put on one concept over another, e.g., selection vs. variation vs. neutral evolution). Biology is thus not a discipline of *scientific* *revolutions*, but of *syntheses*, with *The Modern Synthesis* receiving the most attention (and equal *misunderstanding*) because it was our founding synthesis—but we have progressed theory a lot since then.

One reason why we have seen so many syntheses in the history of biology, and why we see the rising tensions today, is because of the subject matter we investigate. Biological systems are singular in their causal complexity. Biological causation is context-dependent because the phenomena we explore are extremely variable in space and time (why there are no such things as *laws* in biology). Our causation also tends to be multifactorial, multilevel with upwards and downwards causation between biological levels of organization, with a myriad of evolutionary variables (e.g., life-history, population dynamics) that affect biological features in the present (see for more Mitchell, 2003). Add onto this the notion of *reciprocal causation*, that organisms influence their environment and *vice versa*. Biological causation is indeed very *messy* (see for more Anjum & Mumford, 2018).

Such causal complexity invites the divergence of various subdisciplines. Causal ideas arrive from many places in biology, precisely because we investigate the same causal phenomena from various perspectives (e.g., *adaptation*) using different methodologies (e.g., ecology vs. microbiology). In her brilliant book *Idealization* (2017), philosopher of science Angela Potochnik convincingly demonstrates how and why scientists selectively attenuate their research agendas to a particular cause or causal pattern of interest. Their investigations result in the construction of over-simplified and idealized causal models, that disregard other important causal information that lie outside of their chosen periphery. Perhaps no other science is this better appreciated than biology. Biologists routinely over-emphasize and/or neglect key causal information that lie outside the traditional scope of their discipline, due to the messy causation inherent to biological systems, which results in continuous calls for theoretical progress and new syntheses (whether they are founded or unfounded).

In the case presented here, I believe there is a significant place for evo-devo to make great insights where population genetics has overstepped and limited their research focal. But on the other hand, evo-devo has, in many ways, overstepped its boundary and neglected important causal information deriving from modern genetics and ecology. To explain such a causally complex world as we have in biology, we likely need an integrative pluralism (Mitchell, 2003; 2009). But in the instance of evolvability, before we can reach any such integrative point, we firstly need *a restrictive pluralism* to identify the core causes of evolvability.

This is why proponents of the EES are right to call out the fact that biological theory is having a hard time keeping up with the waves of new evidence coming in from all walks of biology (e.g., Uller & Laland, 2019). There is no question that we do need new explanatory and theoretical strategies to explain the causal complexities that are only just being revealed by our superior empirical methodologies.

Yet I see this as a symptom of the scientific process in general, and not something that is terribly specific to biology. Technological progress over the past half-century has led to a dramatic increase in knowledge in every scientific discipline, which is consequently having a hard time being translated back into theory. For this reason alone, I have a growing suspicion that the rising dissension between biologists has less to do with metaphysical or epistemological concerns, and more to do with the inadequacies of how the scientific process is structured itself.

For example, we still communicate and verify science using nearly the same journal system as we did 350 years ago. Such methods were suitable for knowledge production and dissemination back in the time of snail-mail and when ‘horsepower’ actually pertained to horses. But in our modern context, these methods are due reformation. With the amount of new information constantly being turned out by the scientific machine, theoretical progress is stalled by having such a slow uptake process and no unified set or standard for theory to become concretized and/or upended.

Scientific fact and theory are based on consensus, yet we have no practical means for surveying the opinions of scientists, despite living in a technologically capable world. Scientists must resort to reading between the lines of esoteric and extensive literatures, quite literally guessing where theory currently stands. Until this issue is resolved then every scientific theory can expect repeated and unwarranted attacks, especially in evolutionary biology.

The abstractness of evolutionary theory lends itself to more attacks than perhaps any other scientific theoretical structure (as implicitly noted by Welch [2017], Futuyma [Chapter 13]). Evolutionary theory is too esoteric for any scientist working outside the traditional scope of evolutionary biology to pick up our literature and understand where our knowledge currently stands and how it maps back into theory (perfectly exemplified by those esteemed biologists who found success in their respective discipline and mistook their success for knowledge of evolution, i.e., “*The Third Way of Evolution”*). Students of evolution do not know where evolutionary theory currently stands because *we as a discipline do not know where our theory currently stands.*

Indeed, I think that these intellectual battles are to the benefit of science and scientific theory. Still, it would be helpful to have a standardized representation of theory that scientists could continually argue and update, that happens outside of the traditional bounds of “normal science” or empirical efforts.

The main issue, then, is not the fault of progressives or conservatives, but the scientific process in general. Biological theory mimics the phenomena we study; we have an ever-changing, amorphous theory. Slight theoretical modifications are constantly “being added” or advocated, but are they being understood or integrated? Because we have no good means of surveying the opinions of scientists, scientists are constantly shooting at an ever-changing and imperceptible theory, literally guessing where the edges of theory lie. If we had a set or standard for forming and maintaining theory, then this would allow for more accurate critiques and streamline theoretical progress. Therefore, modern science needs a massive makeover, or else the history of science will continue to be one of slow, ineffectual theoretical progress, as demonstrable by the history and present of *evolvability*.

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1. Although mutations were known to be sometimes caused by external but non-selective forces such as UV radiation or the application of other environmentally induced lethal mutagens. [↑](#footnote-ref-1)
2. Poole *et al.* (2003, p. 163) made the claim that “The concept of evolvability covers a broad spectrum of, often contradictory, ideas. At one end of the spectrum it is equivalent to the statement that evolution is possible, at the other end are untestable post hoc explanations, such as the suggestion that current evolutionary theory cannot explain the evolution of evolvability”. Evolutionary theory, and in particular natural selection theory, is not equipped to explain the existence of higher-level selective features such as evolvability. [↑](#footnote-ref-2)
3. Like most things in biology, there is some phenomological overlap between non-genetic and genetic evolvability mechanisms. Genetic variation is not only maintained and conserved by sex, but also by developmental mechanisms which sometimes releases cryptic genetic variation. In another sense, sexual processes could even be considered developmental mechanisms. [↑](#footnote-ref-3)
4. The assumption “phenotypic variation is the selectable material of natural selection” underdetermines the causation of natural selection, and in many considerations, runs parallel to the *random variation assumption* mentioned at the start, since it assumes that genetic mechanisms are stochastic and selectively unimportant. [↑](#footnote-ref-4)
5. Most of the non-genetic mechanisms mentioned by Payne & Wagner (2018) mary be better served under the conceptual umbrella of *phenotypic plasticity*—or the ability of an organism to change its phenotype in response to changes in the environment (Pigliucci, Murren, & Schlichting, 2006, p. 2363). Phenotypic plasticity mechanisms are genetically ingrained mechanisms *that reflect non-genetic adaptive changes*. Every mechanism that these authors have thus classified as non-genetic ‘evolvability mechanisms’ functions better under the concept of phenotypic plasticity since their evolvability-related effects are rather transient in comparison. [↑](#footnote-ref-5)
6. The underlying causal mechanisms governing these processes are not well understood, and they may as well be the result of genetic contributions (Merila & Hendry, 2013; Birney et al., 2016; Lappalainen & Greally, 2017). We are thus left to assuming some amount of epistemic risk when we claim to know the causal basis for the observed phenotypic heterogeneity. [↑](#footnote-ref-6)
7. Constant, Invariable, or stochastic genetic evolution is often a presupposition for other failed notions such as the random variation assumption or the molecular clock. [↑](#footnote-ref-7)
8. Relating to causal specificity, most students of evolvability are the first to recognize how little is still known about the underlying mechanisms of the G-P map, or how genetic variation is turned into phenotypic variation. There seems to be an element of *epistemic* and/or *aleatory* risk involved with accepting evo-devo conceptions of evolvability (in a similar but less-dire case as that presented by Biddle, 2015). The ontological causal relationship between non-genetic evolvability mechanisms and their ensuing evolvability-related effects remains a major question mark. This suggests that non-genetic mechanisms may be less causally specific than genetic evolvability mechanisms since we have a clear causal relationship between genetic evolvability and its effects on adaptation. [↑](#footnote-ref-8)
9. The distinction made here is similar to what Mackie [1965] refers to as the predisposing causes (causal conditions that set the stage for an event to occur) from triggering causes (causes that trigger the

   event’s occurrence), which is a common distinction made in the medical literature (e.g., smoking increasing the probability of causing cancer). [↑](#footnote-ref-9)
10. This is also a likely reason why evolvability was initially built within evolutionary theory and neglected for so long. [↑](#footnote-ref-10)
11. In no other science, I think, is this better appreciated than in biology due to the immense conceptual and phenomenological overlap. [↑](#footnote-ref-11)
12. There are, however, several aspects of genetic evolvability that are *incoherent* with our existing theory, and excitingly, this is where theoretical progress should happen. The reductive atmosphere that born the modern synthesis and modern evolutionary theory has been, time and time again by ecology, proven to be too abstract and unrealistic of natural parameters. We must move towards a pluralistic, multilevel, multicausal model of natural selection if we wish to explain complex adaptations, like those surrounding genetic evolvability (i.e., sex and adaptive mutation; see for more Distin, *forthcoming*). For these reasons, we must conserve several remnants of genetic theory, such as *Weismann’s barrier*, while calling for the general theoretical progress away from the reductionistic causal modeling of biology old. [↑](#footnote-ref-12)