

(2003) Pp. 52-61. In: *Keywords and Concepts in Evolutionary Developmental Biology*. B. K. Hall and W. M. Olson (eds.). Harvard University Press, Cambridge, Mass.

so elusive and how we might more effectively apply it. We believe that the central problem of constraint is a general failure to recognize its relativism. By relativism, we mean that constraint is only sensible within a local context (Stearns, 1986; Gould, 1989b; Schwenk, 1995; Fusco, 2001). Its meaning and appropriate invocation therefore depend on the specification of several factors that define the circumscribed realm within which it is applicable. Specifying factors include a designated clade (an in-group), a particular character or set of characters, a focal life stage, and most importantly, a null model. As these factors can change case by case, both the nature of constraint and the validity of its invocation can change as well. Attempts to define constraint in absolute or universal terms, as is typically done, are thus foredoomed.

Relationship to Selection

Contention and confusion surrounding constraint's relationship to selection illustrate the importance of relativism in characterizing constraint. Starting with Gould and Lewontin (1979), one view sees constraints as manifested in their effects on selection, implying that constraint is one thing and selection another. This dichotomous approach has been amplified to suggest that selection must be disallowed altogether as a cause or mechanism of constraint (e.g., Schwenk, 1995; Schlichting and Pigliucci, 1998). If not, it is argued, a well-understood process (selection) is replaced with a cryptic label (constraint), thus opening the door to "pseudoselection" and the dilution of the concept.

Another school of thought, however, does exactly this. By identifying constraint with a particular evolutionary outcome or pattern, the responsible mechanism is, by definition, "constraint." For example, a pattern of phenotypic stasis is often taken to imply that something has "constrained" phenotypic evolution in the characters of interest. If the cause of this limitation is stabilizing selection or conflicting environmental selection pressures, these are labeled "selective" or "ecological constraints," respectively. Constraint and selection are thus conflated.

Because this latter approach could quickly get out of hand, we should eliminate redundancy by making constraint and selection mutually exclusive. This goal is not so easily achieved, however. Maynard Smith et al. (1985), for example, adopted a dichotomous view in their classic treatment of developmental constraints. They wrote: "We would like to know whether [stasis] reflects developmental constraints limiting the

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Constraint

Constraints are mechanisms or processes that limit the ability of the phenotype to evolve or bias it along certain paths. Beyond this general statement, however, little is agreed upon or clearly understood about constraints (see overviews by Gould and Lewontin, 1979; Alberch, 1982; Maynard Smith et al., 1985; Gould, 1989b; Wake, 1991; Amundson, 1994; Raff, 1996; Arthur, 2001; Burd, 2001; Schwenk, 2002). Ambiguity about constraint stems, paradoxically, from its very popularity. Spurred by Gould and Lewontin's (1979) influential critique of "adaptationism," evolutionists have embraced constraint enthusiastically, but not always critically. Thus, to a large extent, the facile assumption of constraint has merely replaced the facile assumption of adaptation. Coupled to an explosive proliferation of terminology, such uncritical usage has led to increasingly idiosyncratic meanings for constraint so that the concept is of diminishing value in scientific discourse (Antonovics and van Tienderen, 1991; McKittrick, 1993; Schwenk, 1995; Schlichting and Pigliucci, 1998).

If, as some claim, the constraint concept is moribund, it is only because the concept is so difficult to operationalize. Nonetheless, in capturing the growing sense that not all evolutionary outcomes are equally probable, constraint remains a central, even critical, element of evolutionary theory. It is therefore worth asking *why* the constraint concept is

context in which constraint is to be applied, a task to which we now turn.

Context of Constraint

Owing to constraint's relativism, a set of "fixed" points must be established around which constraint can be organized. These points, or specifying factors, serve to anchor the concept so it can be meaningfully defined. As a metaphor, consider the example of an unrooted phylogenetic tree. Until the tree is rooted by specification of an outgroup branch, several patterns of historical relationship are possible. The root anchors the tree and determines the order of the branching. Similarly, the following specifying factors anchor the context of constraint so it can be characterized in a given situation. Although some of these factors are implicit in the constraint literature, most are rarely, if ever, treated explicitly.

Time frame. Time frame is relevant to constraint in two ways. First, evolutionary constraints are manifested over long time periods (geological rather than ecological scales). Thus, a quantitative genetic approach, for example, may give only limited insight into the long-term potential for constraint (Arnold, 1992). On the other hand, given enough time, most constraints are eventually broken or circumvented. Constraints are therefore historically stable, but ultimately mutable (Schwenk, 1995; Wagner and Schwenk, 2000).

Historical pattern. Because constraints are manifested over geological time, a mechanistic hypothesis of constraint is best tested by reference to a historical pattern predicted as its consequence (McKittrick, 1993; Schwenk, 1995; Schwenk and Wagner, 2001). Patterns putatively associated with the past action of constraint include long-term phenotypic stability or stasis in characters, the observation that only a subset of theoretically possible phenotypes has evolved, the repeated independent evolution of a certain phenotype within a clade (parallelism), and the failure to achieve an "optimal" phenotype according to mechanical or engineering analyses.

Historical patterns are only weak tests of constraint hypotheses; alternative mechanisms can lead to similar patterns (e.g. Schwenk and Wagner, 2001). To be meaningful, the test requires comparison of "constrained" to related, "unconstrained" clades in which evolution has proceeded according to the expectations of a null model. There are,

possibility of change or, conversely, the maintenance of uniformity by stabilizing selection." How can the effects of constraint, they wondered, "be distinguished from the action of natural selection" (p. 266)? This partitioning of selection and constraint is significant in light of their definition of developmental constraints as "biases on the production of variant phenotypes or limitations on phenotypic variability caused by the structure, character, composition, or dynamics of the developmental system" (p. 265). This definition implies that constraints act during development to limit the generation of phenotypic variation, thereby limiting the pool of variation upon which selection can act. This approach is compelling because, by distinguishing the generation of variation from the operation of selection on that variation, Maynard Smith et al. seem to provide a logical basis for conceptually separating constraint and selection.

At least two mechanisms, however, probably cause "biases on the production of variant phenotypes": (1) Variations fail to arise in the first place because underlying genetic or epigenetic variation is not expressed phenotypically. Development, in this case, acts as a buffer ensuring consistency in a character's phenotype despite variation in the background information or developmental milieu—a process that is referred to as *canalization*. (2) Variations arise during development, but disruptions to developmental dynamics cause the death of the embryo and the variant characters never enter the population. This case represents nothing more than viability selection acting on early life stages. Thus, Maynard Smith et al.'s definition is not consistent with their dichotomous view; the failure to generate phenotypic variation during development (a putative developmental "constraint") cannot be temporally or mechanistically separated from the action of selection. Once again, constraint and selection are conflated.

Our inability to reconcile selection and constraint in this example stems from adherence to an absolute definition of constraint—in this case, one that would universally exclude selection. Followed to its logical conclusion, this dichotomous approach leads to a highly restrictive notion of constraint (Schlichting and Pigliucci, 1998) that does not satisfy the needs of many evolutionists for a constraint concept. With a relativistic approach, however, a potential solution emerges: selection might sometimes act as a constraint, but only in particular circumstances. These circumstances are determined by specification of the local

however, philosophical objections to any inference of past processes and selection pressures based on current conditions and patterns (Reeve and Sherman, 1992; Leroi et al., 1994). Given that hypotheses of constraint require exactly such inferences, their support is necessarily circumstantial—an operational reality that need not invalidate the concept.

Character specificity. A hypothesis of constraint applies to a designated character or set of characters, not to whole organisms (Schwenk, 1995). This is necessary both for precision and to avoid the paradox of simultaneous constraint and adaptation. Character constraints are thus decoupled from their ultimate effect on the state of organismal adaptation and lineage success. In other words, characters can be evolutionarily limited, but the effect of this limitation on organismal function and evolution can be neutral, positive, or negative (Wagner, 1988; Roth and Wake, 1989).

Clade specificity. Constraints are attributes of living systems and as such, they arise, evolve, and eventually disappear. In other words, constraints have phylogenetic continuity. At any given time, therefore, the organisms within a clade encompass a unique set of character constraints. A constraint hypothesis thus applies to characters within a particular clade at a particular time. This excludes from consideration universal attributes of life, such as a nucleic acid-based information system and conformation to physical laws. While such factors undoubtedly circumscribe the range of possible phenotypes—elephants cannot have spindly legs—they have less explanatory value for interpreting one evolutionary outcome over another within a particular clade.

This observation has several implications. First, for a given clade in which a constraint is hypothesized to exist, there must be a related clade without the constraint. Without the ability to compare character evolution in constrained and unconstrained clades, there is no possibility of falsifying the hypothesis. Second, given clade specificity, the historical stability of constraints, and their eventual dissolution in descendant taxa, constraints are distributed monophyletically or paraphyletically. Mechanistically similar constraints might arise polyphyletically, but these would be nonhomologous. Finally, so-called phylogenetic constraint, as typically used, merely implies historical contingency, not character constraint. It calls attention to the starting condition, which certainly influences evolutionary outcomes given that selection acts on existing phenotypic variation; but it does not speak specifically to the question of whether a particular character is constrained. Certainly con-

straints, like other organismal attributes, are part of a lineage's legacy, but historical contingency is a universal attribute of character evolution and does not, therefore, satisfy the requirement of clade specificity for hypotheses of constraint.

Focal life stage. The focal life stage is the designated life stage in which character evolution is putatively constrained. Typically, this is the adult stage, as implicit in most studies; but it can be any stage of ontogeny. Recognition that constraints are manifested at a particular life stage permits the decoupling of constraint from a particular mechanism because any mechanism that limits the ability of focal life stage characters to evolve according to the null model is potentially a constraint. For example, if the null model is evolution by natural selection, constraints are manifested by *their effects on selection acting during the focal life stage*. Designation of a focal life stage would help to resolve the problem of circularity encountered in the Maynard Smith et al. (1985) example.

Internal vs. external selection. The fitness consequences of character variation are traditionally seen as determined by the biotic and abiotic environment surrounding an organism. Environmentally imposed selection pressures act on characters to maintain the fit, or state of adaptation, between phenotype and environment. However, character variants are also tested within the internal arena of a functioning organism. Stabilizing selection pressures in this case stem from the dynamic interactions among characters, either in the instantaneous sense of function or in the sequential sense of development. Variants that disrupt the internal dynamics of functional or developmental systems have negative fitness consequences for the organism.

These components of selection are distinguished as external and internal selection, respectively (Whyte, 1965; Riedl, 1977; Cheverud, 1984, 1988; Arthur, 1997, 2001; Wagner and Schwenk, 2000; Fusco, 2001). The critical distinction for our purposes is that external selection changes with environment, whereas internal selection remains essentially constant because it travels with the organism. Thus characters are likely to be subjected to long-term, internal stabilizing selection imposed by intrinsic, organismal, functional integration, even as the external environment changes. If internal selection opposes external selection, the potential for constraint is clear. Such long-term stabilizing selection is, furthermore, likely to limit the pattern of variation available to external selection through its influence on the genetic variance/covariance matrix (Cheverud, 1984, 1988).

Null model. A null model represents an expectation concerning how character evolution would proceed in the absence of constraint (Gould, 1989b; Antonovics and van Tienderen, 1991; Schlichting and Pigliucci, 1998). Different models lead to different notions of constraint (Amundson, 1994; Schwenk, 2002). For example, implicit in most studies of nucleotide sequence evolution is a null model of neutral evolution, implying random mutation and fixation by drift. The expected pattern is a constant rate of sequence evolution, equal to the neutral mutation rate, and sequence divergence among taxa. A sequence that is highly conserved among taxa deviates from the null expectation and is said to be "constrained," meaning that it is under stabilizing selection (e.g., a change in nucleotides would entail harmful functional effects).

In contrast, a null model of evolution by natural selection is implicit in most organismal studies. The failure of the phenotype to have evolved in response to selection is then taken as evidence of constraint. Selection, in this case, is logically excluded as a mechanism of constraint (the dichotomous approach). Conflicting conclusions about the nature of constraint thus result from different null models. What is the best null model for constraints on phenotypic evolution?

It is reasonable to assume that, in the absence of constraints, phenotypic evolution would proceed according to the Darwinian notion of adaptive evolution by means of natural selection. An adaptive fit between phenotype and environment is driven by the external component of selection. Therefore, an appropriate null model for constraint is the adaptive evolution of characters by means of external selection.

A Definition of Constraint

Given the specifying factors, we can define constraint as a mechanism or process that limits or biases the evolutionary response of a character to external selection acting during the focal life stage. "Limits" and "biases" are usually identified post hoc by comparing patterns of character evolution in putatively constrained and unconstrained clades. In the latter, character evolution should conform to the null model; in the former, it should deviate from the model as predicted (e.g., Schwenk and Wagner, 2001).

This definition reconciles constraint and selection because its relativism accommodates the dichotomous view by suggesting that constraints are manifested in their effects on selection while allowing selection itself

to serve as constraint. This is possible because internal selection acting at earlier life stages can limit the variation available to selection at the focal stage, and because internal selection can oppose external selection during the focal stage.

Types of Constraint

We have emphasized a context for constraint that leads to a workable definition. We are less concerned with compiling a list of possible constraints because these must be argued case by case. However, we consider briefly the potential nature of these constraints. The typological labels associated with most treatments of constraint are problematic due to definitional ambiguity and absolutism. Are genetic correlations caused by the epigenetic system genetic or developmental constraints? Does functional integration of developmental processes lead to developmental or functional constraint? We therefore stress mechanisms over labels. Our list may not be exhaustive.

Constraints are mechanisms that affect the evolutionary response of a trait to external selection acting at the focal life stage such that, over the long term, it deviates from null model expectations. Most constraints act at earlier life stages to restrict phenotypic variation of the trait within a population at the focal life stage, but some act during the focal stage to limit the efficacy of external selection acting on the trait. Possibilities include:

1. *Variational inaccessibility.* Despite mutations, certain character variants are never produced. These variants are therefore developmentally impossible to achieve and are never introduced into a population. This is implied by canalization and has been called both genetic and developmental constraint.
2. *Developmental lethality.* In this case, character variants can be produced, but their introduction into the developmental stream is lethal to the embryo. Lethality is caused by disruption to developmental dynamics and is therefore a case of internal selection. This has been called *developmental constraint*, but it is rarely attributed to selection.
3. *Deleterious pleiotropic effects.* In contrast to (2), individuals with variant character phenotypes survive until the focal life stage, but always suffer lower fitness because of deleterious changes in correlated characters (Galis, 1999; Galis and Metz, 2001). This has been called *genetic, epigenetic and developmental constraint*.

4. *Functional integration.* Functional integration implies internal stabilizing selection stemming from the dynamic interaction among characters during system function (Witte and Döring, 1999; Wagner and Schwenk, 2000). This can be manifested as constraint in two ways. First, a character variant is developmentally produced, but causes lethality at a later life stage when the relevant system becomes functional. For example, a modified dental character in a mammal might so reduce the efficacy of mastication that the afflicted individual starves to death, but only after weaning when it must eat solid food. This character variant fails to reach the adult focal life stage. Alternatively, variant individuals survive to the focal stage, but the variant character is always associated with lower fitness. Both situations have been called *functional constraint*.

Finally, our definition would seem to allow a final notion of constraint as the action of external selection during earlier life stages to limit variation available at the focal stage. In most species, for example, there is strong external selection on juveniles and relatively few survive to adulthood. A great deal of variation is therefore eliminated from a population during early life stages, possibly constraining the effects of external selection acting during the adult stage. However, this concept violates the important premise that constraints have phylogenetic continuity. External selection acting on juvenile stages results from a particular phenotype-environment interaction and is therefore not a property of the evolving clade. To the extent that juvenile adaptations evolve, including developmentally and functionally integrated character complexes, the efficacy of external selection acting at later stages will be reduced through the processes outlined in this entry. Metamorphosis is considered to be an evolutionary escape from such life stage-specific constraints (e.g., Moran, 1994).

Our goal has been to derive a biologically defensible and internally consistent concept of constraint that is applicable to a range of evolutionary interests. There can be no claim of a single, correct solution to this problem. The definition and types of constraint that we outlined follow directly from the factors we specified, but other definitions are possible if one or more of these factors are changed—for example, if a different null model is specified. The strength of this formalization is its ability to accommodate other needs or viewpoints.

By translating random genetic mutations into usable variation and ensuring the maintenance of a functionally coherent internal milieu, constraints act as regulators that tune or modulate the types of variation available to selection over time in a way that may facilitate adaptive evolution (e.g., Cheverud, 1984; Wagner, 1988; Wagner and Altenberg, 1996). Thus, while constraints imply evolutionary limitations on characters, their ultimate effect on organismal evolution may not only be positive but essential.

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