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Beyond Optimization: Legaliform (Law-like) Principles and Bounded Rationality in Lithic Technology

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Abstract

This article proposes a formal epistemological and methodological framework for the analysis of lithic technology, moving beyond traditional optimization-oriented models and normative typologies. Grounded in Mario Bunge's socio-natural science and Herbert Simon's theory of bounded rationality, we introduce the concept of legaliform (law-like) principles. These principles are defined as stable, necessary relationships between technical procedures and morphological outcomes, dictated by the physics of brittle fracture and enacted through procedural memory. To enhance analytical precision and cross-cultural comparability, we develop a semi-formal symbolic notation that identifies the core "techno-scientific" operators underlying lithic reduction. We argue that stone tool morphology is not a static reflection of a "mental template," but a dynamic sequence of technically adequate states achieved through satisficing behavior. By framing these legaliform regularities as epistemological meta-standards, this article establishes a standardized framework for data reproducibility, verification, and quality control in technological analysis. The framework identifies eight primary legaliform principles—including bifacial reduction (PBR), thermal alteration (PTT), and maintenance and reactivation (PMR)—illustrating how they structure technical action under material and cognitive constraints. The utility of this approach is demonstrated through a case study of Paleoindian Fell projectile points in South America. By operationalizing the Maintenance and Reactivation Principle (PMR), we explain the high morphological variability of these points as a predictable result of life-history and functional restoration rather than cultural "drift" or failed design. This perspective provides a rigorous basis for identifying Guided Convergence in the archaeological record, offering a scientific alternative to diffusionist explanations and purely morphological comparisons that often overlook the underlying techno-scientific regularities of lithic practice.

Keywords: archaeological theory; epistemology; middle-range theory; lithic technology; legaliform principles; bounded rationality; reduction sequences; experimental archaeology; actualistic studies; Fell points



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1. Introduction

The recurrence of specific technical procedures and morphological configurations in lithic technology has historically been interpreted through models that privilege functional optimization or adaptive responses to environmental constraints. Within influential optimization-oriented frameworks, prehistoric technical decisions are often conceptualized as rational choices aimed at maximizing efficiency, durability, or raw material economy (e.g., [1–4]). While these models have provided essential tools for understanding technological organization, their generalized application often presupposes agents endowed

with levels of calculation and global planning that are difficult to reconcile with the actual conditions of lithic practice.

As noted by Hussain and Will [5], the implicit figure of the knapper as an “engineer” becomes problematic when confronted with the inherent uncertainty of raw materials and the frequent interruption of reduction sequences. In many cases, technical action resembles more a process of situated adjustment rather than the execution of a rigid, idealized design, a perspective traditionally emphasized in classic optimization models [6–8]. This perspective aligns with 4E cognitive science (Embodied, Embedded, Enacted, Extended), where technical intelligence is seen as a situated interaction between agent and material rather than a top-down mental template [5,9–11]. In archaeology, this approach has been specifically developed through Material Engagement Theory [12], suggesting that the ‘mind’ of the knapper extends into the stone itself during the act of flaking.

This situated interaction is further constrained by the deterministic nature of brittle fracture mechanics. As argued by Pelcin [13,14], the relationship between platform thickness, exterior platform angle, and flake mass is not a matter of cultural choice, but a physical law of lithic reduction. Consequently, the knapper’s agency is exercised within a ‘design space’ where legaliform principles act as boundary conditions, transforming abstract goals into technically viable solutions through iterative adjustments [15,16].

This empirical variability has led some researchers to suggest that the concept of a “finished product” is a fallacy, arguing that artifact morphology is merely a transient point in a continuous process of reduction and maintenance [17,18]. However, we contend that while reduction is indeed continuous, it is not unstructured. From a socio-natural science perspective [19], lithic technology emerges from the intersection of physical laws—specifically the mechanics of brittle fracture [20,21]—and socially transmitted technical practices. Within this interaction, certain “law-like” regularities emerge. We define these as legaliform principles: stable, necessary relationships between technical operations and morphological outcomes that structure the space of technical possibilities.

Rather than assuming global maximization, these principles operate under the framework of bounded rationality and satisficing behavior [6,22]. A knapper does not need to calculate the optimal flake geometry; instead, they rely on procedural memory and embodied routines that have proven “good enough” to achieve technical adequacy across generations. While some authors have argued against the existence of intended forms, we maintain that legaliform principles allow for the recognition of technically adequate states [23], distinguishing necessary technological regularities from historically contingent cultural choices.

This approach builds upon a long and rich history of methodological analyses directed toward artifact classification. In the European tradition, the foundational typological frameworks established by Bordes [24] and later expanded through the structural and technological insights of Tixier et al. [25] and Inizan et al. [26] provided crucial systematic tools to categorize empirical variability. Concurrently, the development of the *chaîne opératoire* concept [27–29] shifted the focus from static formal categories to dynamic reduction trajectories. In North America, a parallel and highly influential tradition deeply explored lithic reduction sequences (usually heuristically described using stages) to reconstruct the step-by-step technological life history of artifacts (e.g., Holmes [30], Crabtree [31], Muto [32], Callahan [33]). Alongside these reduction models, evolutionary and processual approaches independently formalized technological organization models to evaluate raw material economy and landscape use (e.g., [34–36]). While these diverse classification and technological methodologies are fundamental to the history of research, they frequently operate at descriptive or historical levels. The legaliform framework proposed here does not aim

to replace these traditional classifications, nor does it present merely another descriptive typology. Instead, it seeks to identify the universal nomoprismatic substrates—grounded in Mario Bunge’s socio-natural ontology—that underlie and clarify the physical boundaries within which all historical traditions and reduction strategies necessarily operate. Consequently, this approach provides a robust theoretical mechanism to explain guided convergence: the independent emergence of similar technological solutions across diverse cultural and environmental contexts, driven by shared material constraints rather than direct historical transmission alone.

From a broader methodological standpoint, the definition of these principles addresses a critical requirement within the philosophy of science and metrology: the need for theoretical standards before empirical verification can take place. As argued by Ernst Nagel [37] in his classic treatise *The Structure of Science*, the establishment of stable, law-like relations is a prerequisite for generating invariant criteria of explanation across different domains of observation. In the field of standardization and measurement, this conceptual priority is fundamental. Hasok Chang [38], in examining the philosophy of metrology, demonstrated that the creation of any practical instrument, baseline, or technical standard depends entirely on pre-existing nomological principles—that is, stable laws of nature that guarantee the consistency of the properties being measured. In lithic studies, the physics of brittle fracture acts as this objective natural baseline. Therefore, legaliform principles function as epistemological meta-standards: foundational conceptual structures that regulate how archaeological data is classified, verified, and audited globally, ensuring that technological descriptions are not merely subjective taxonomies but reproducible scientific records.

2. Theoretical Foundations: Legaliform Principles and Bounded Rationality

2.1. The Epistemology of Legaliform Statements

The term “legaliform” (law-like) is adopted here from the scientific–philosophical framework of Mario Bunge [39,40]. In Bunge’s ontology, a distinction is made between laws (the objective patterns of nature) and law-like statements (the conceptual reconstructions of those patterns). In line with the tripartite nature of technological knowledge [41], we distinguish between cultural “recipes for action” (the socially transmitted ‘how-to’) and the underlying “techno-science”. While recipes are historically and culturally contingent, legaliform principles constitute the nomoprismatic rules of that techno-science: they describe the necessary mechanical relationships that must occur for any technical goal to be successfully realized.

This addresses the problem of equifinality: while different cultural recipes or gestures can be used, the underlying mechanical relationship ($V_i + A_{alt} \rightarrow S_{bi}$) remains a structural necessity dictated by the physics of stone [21]. Legaliform principles thus act as an intermediate level of analysis [42] that bridges low-level descriptions of flakes and high-level behavioral theories. To visualize how these analytical scales are organized epistemologically, Table 1 outlines this tripartite hierarchical framework.

Table 1. Hierarchical framework of lithic analysis.

Analytical Level	Domain/Scope	Components
High-Level	Behavioral & Historical	Cultural traditions, social learning, environmental adaptation.
Intermediate	Legaliform Principles	Techno-science: Nomoprismatic rules (P_{BR} , P_{TT} , MR , P_{UX} , P_{PC} , etc.)
Low-Level	Descriptive Domain	Reduction sequences / <i>Chaînes opératoires</i> , specific tool types, metric variation.

2.2. Bounded Rationality and the “Satisficing” Knapper

To understand how these principles are activated, we move away from the idealized “engineer” model. Herbert Simon’s [6,22] concept of bounded rationality provides the necessary framework. In the real-world practice of knapping—characterized by internal flaws in raw materials, limited time, and incomplete information—agents do not maximize in a global sense. Instead, they *satisfice*: they select the first available technical solution that meets a situational threshold of adequacy. This explains why many lithic assemblages show “interrupted” sequences that are nonetheless functional, a fact often overlooked by normative typologies that seek idealized end-products.

2.3. Procedural Memory and Emergent Form

The activation of legaliform principles relies on procedural memory—the embodied, sensorimotor knowledge acquired through practice and repeated interaction with materials [23,43]. This “sedimentation” of technical skill (as termed in phenomenological and ecological cognitive perspectives) explains why similar technological configurations recur across geographically and historically distant assemblages. What recurs is not necessarily a cultural template, but the repeated activation of structurally constrained solution spaces—a process of guided convergence.

3. Methodology: A Formal Notational Language for Lithic Analysis

The adoption of a formal notation in this study is grounded in an explicit epistemological position. Following the systemic and materialist ontology of Mario Bunge [44,45], archaeology is defined as a socio-natural or bio-social science. This hybrid status arises because the archaeological record is not merely a collection of cultural symbols, but the result of metabolic and technical interactions between biological organisms and their physical environment. These ‘fossilized’ remains of human behavior are further shaped by natural site-formation processes—chemical, physical, and biological—operating over centuries or millennia [46].

Within this framework, the legaliform principles presented here are not the product of detached contemplation or mere morphological observation. Instead, they constitute the cumulative result of more than 40 years of systematic experimentation and actualistic research, involving continuous interaction with a wide range of academic and amateur knappers (e.g., [47,48]). Experimental archaeology is thus understood as a basic actualistic science grounded in the physico-chemical properties of lithic materials and the mechanical techniques required to transform them into cultural artifacts [49].

Following the classic distinction made by Claude Bernard [50], experimentation differs fundamentally from passive observation; it is a controlled intervention aimed at uncovering the stable cause-effect relationships of fracture mechanics. As a middle-range discipline, experimentation allows for the derivation of these principles at an intermediate analytical level [42,51]. Consequently, the use of a symbolic notational language is a methodological requirement to represent the legaliform regularities that emerge from this intersection. To facilitate the comparison of technological processes and to reduce the ambiguity of qualitative descriptions, this study employs a semi-formal symbolic notation. This system provides a standardized ‘algebra’ of reduction, making explicit the operators that connect human action to material results under stable physical and cognitive constraints [13,52].

In the context of knowledge governance and data quality control, this symbolic framework functions as a rigorous protocol for the standardization of scientific observations. As argued by Hans-Jörg Rheinberger [53] in his philosophy of experimental systems, scientific data cannot achieve cross-cultural or international reproducibility if the “epistemic things” under study are described through shifting, impressionistic terminology. Standardization

is achieved when the format of thought and the structural relations of an experiment are made explicit through clear, non-ambiguous directiveness. This approach perfectly mirrors the international consensus on standardization established by the International Organization for Standardization and the International Electrotechnical Commission (ISO/IEC Guide 2:2004), which defines a standard not merely as a mechanical specification, but as a repeatable conceptual framework designed to achieve an optimum degree of order in a given context. By translating qualitative reduction sequences into an explicit, semi-formal symbolic notation, this article provides a standardized ‘grammar’ for lithic technology, offering an objective method to audit, verify, and compare technological data globally.

Finally, these principles do not reduce archaeology to a branch of physics or materials science. On the contrary, they serve a strictly anthropological archaeology [54,55]. By identifying the universal physical and biological constraints of lithic production, we can more precisely isolate the cultural variability and the specific social choices made by prehistoric agents. Understanding the ‘how’ of technical necessity allows us to better interpret the ‘why’ of human behavior. Thus, this formalized approach provides the necessary analytical substrate to study the evolution of human cognition, the social transmission of technological knowledge, and the diverse adaptive strategies of past societies—the core concerns of a truly scientific and anthropological archaeology [56,57].

The use of semi-formal, algebraic-oid notation to model complex qualitative phenomena has a highly successful history outside of archaeological science, particularly in analytical philosophy and the philosophy of science. Most notably, Mario Bunge [58,59] extensively employed mathematical exactification and algebraic state-space schemas in his *Treatise on Basic Philosophy* to define concepts like ‘system’, ‘state’, and ‘transformation’ without relying on quantitative values. Similarly, in analytical philosophy and formal epistemology, researchers regularly use notational schemas and inductive-logical operators to construct rigorous, non-quantified structural arguments, such as evaluating complex historical probabilities or systemic relations (e.g., [60]). By adopting this class of formal notation, archaeology borrows a robust epistemological tool from the philosophy of science. This allows us to formalize the ‘know-how’ and structural steps of lithic technology into logical propositions that can be analyzed, shared, and tested internationally, bypassing the ambiguities of purely verbal descriptions.

Definition of Symbols and Operators

To clarify this symbolic notation for the reader, the algebraic-like equations operate as logical-sequential operators rather than quantitative functions. For example, let us parse the general operator equation representing a reduction sequence step:

$$(V_i \oplus A_{alt}) \rightarrow S_{bi}$$

Here, V_i represents the initial state of the lithic volume (the independent variable undergoing transformation). The operator $\oplus$ denotes the physical application of external energy through a specific technical action (e.g., percussion or pressure), and A_{alt} represents the specific active alterer or tool utilized (e.g., a soft hammerstone or antler pressure flaker). The arrow ($\rightarrow$) functions as a transitional operator indicating physical causation and workflow directionality. Finally, S_{bi} represents the resulting structural state (in this case, a bifacial surface state). By reading the equation from left to right, the reader can systematically follow how a specific initial volume, when subjected to a targeted technical action with a selected tool, is physically transformed into a subsequent, predictable morpho-technical state. This parsing method applies uniformly across all legaliform equations in this paper.

P_x : Label identifying the specific legaliform principle.

V_i : (Initial Volume): Represents the starting knappable lithic unit.

$\oplus$ (Composition/Interaction Operator): Denotes the non-commutative physical interaction between the agent's energy, the tool, and the lithic mass. It implies that the *order* of technical actions affects the final morphological state.

A_x : Action, represents a specific technical gesture or operation (e.g., A_{alt} for alternating removals).

$\rightarrow$ (Technical Necessity/Implication): Indicates that if the preceding actions are met under the laws of physics, the resulting morphological state follows by necessity.

S_x : Sectional Geometry, represents the resulting morphological or sectional state (e.g., S_{bi} for biconvex, S_{pc} for plano-convex).

4. Inventory and Development of Legaliform Principles in Lithic Technology

The identification of legaliform principles in lithic technology does not entail the construction of a closed or exhaustive system. Rather, it involves recognizing a set of recurrent technical regularities that operate across different socio-cultural repertoires, chronological periods, and environmental contexts. These principles constitute general procedurally recurrent responses to recurrent technological problems and form the practical substrate upon which empirical variability is generated.

From the perspective of international technical standards, these principles function as “standard operating procedures” (SOPs) of the prehistoric past. In modern scientific standardization and quality control, a standard is defined by its ability to produce a predictable outcome from a given set of initial conditions (ISO/IEC Guide 2). By formalizing these principles, we are establishing a framework for the interoperability of archaeological data: a way for researchers in different regions to verify if they are observing the same techno-scientific phenomenon based on shared physical and procedural benchmarks.

These principles are best understood as the cumulative outcome of a very long evolutionary history of human interaction with stone, extending from the earliest hominins to the end of the Upper Paleolithic. Their persistence is not accidental, nor does it result from repeated adaptive responses to similar environments. Instead, it reflects the stabilization of technically adequate ways of working lithic materials under universal physical, cognitive, and procedural constraints. The validation of these principles as law-like statements requires a rigorous process of empirical testing and contrastation [45], which in this framework is provided by actualistic and experimental research.

The inventory presented below is necessarily provisional and open to further expansion. Its purpose is explanatory rather than classificatory, illustrating how a limited set of legaliform principles structures lithic production through satisficing mechanisms, rather than through global optimization strategies.

The approach proposed here operates at an intermediate analytical level [42,49,51,54,57]. It goes beyond low-level descriptive accounts of artifact morphology and reduction sequences, while providing the mechanical and procedural substrate that high-level optimization models typically presuppose but rarely specify. Legaliform principles articulate how stoneworkers manage the physical constraints of fracture mechanics [20,21,61] through satisficing strategies, producing technically adequate solutions under conditions of bounded rationality rather than through global planning or optimization. Technological choices are further constrained by the availability, quality, and distribution of raw materials, which structure but do not determine reduction strategies [36].

From the perspective of traditional technological knowledge, the recurrent management of fracture mechanics involved in lithic reduction corresponds to what Schiffer and Skibo [41] have termed techno-science: a body of practical, often tacit knowledge grounded

in the physical and mechanical properties of materials, even when not articulated in formal or theoretical terms [43,62]. Although prehistoric toolmakers did not possess an explicit scientific understanding of fracture mechanics, their technological actions consistently operated within its constraints, exploiting stable cause–effect relationships between raw material properties, platform configuration, force application, and flake propagation through practice rather than abstract reasoning. In this sense, the legaliform principles proposed here do not describe culturally transmitted recipes for action, nor do they imply conscious analytical reasoning by prehistoric agents. Rather, they constitute analytical, *ex post* formulations that make explicit the necessary techno-scientific regularities underlying lithic production, as these were recurrently exploited under conditions of bounded rationality and satisficing behavior.

At a cognitive level, the recurrent activation of such techno-scientific regularities can be understood in terms of procedural memory. Procedural memory refers to learned, embodied sequences of action acquired through repeated practice, rather than to explicitly articulated or propositional knowledge. In lithic technology, knappers do not apply abstract rules or consciously reason through fracture mechanics at each step; instead, they rely on procedurally stored patterns of action that enable the consistent management of platforms, angles, force application, and core configuration through practice. These learned procedures are socially transmitted and progressively stabilized through experience, forming a practical cognitive substrate for technological action (see also [23]).

This procedural grounding is closely related to embodied cognition. In lithic technology, technical knowledge is not an abstract mental plan but a practical ability that emerges from direct interaction between the knapper's body and the material [12]. Rather than following rigid mental scripts, practitioners engage in a continuous adjustment to the stone's density, internal flaws, and surface angles, as well as to the evolving configuration of platforms, techniques, and force application involved in the reduction process. From a functional perspective, this involves rapid feedback loops in which movements are refined in real time based on the resistance and response of the material [63–65]. Legaliform principles are therefore not “rules” stored in the brain, but stable technical solutions that emerge from the repeated enactment of sensorimotor coordination under material constraints.

Within this framework, legaliform principles do not correspond to explicit mental templates or normative prescriptions but represent analytical, *ex post* formulations of stable regularities that emerge from the repeated enactment of procedurally learned techniques under universal physical constraints and conditions of bounded rationality.

The transition from natural language to a symbolic notation is essential for achieving clarity and precision in scientific reasoning [66]. The symbolic notations used in this comment are not intended as a mathematical formalization of lithic reduction processes, nor as predictive models in a strict sense. Rather, they draw on the tradition of semiformally expressed law-like statements in the philosophy of science, where symbolic languages are employed to make explicit necessary relationships between conditions, operations, and outcomes without implying quantification or optimization. Their purpose is to make explicit necessary technical relationships between minimal material conditions, procedural operations, and recurrent morphological outcomes. In this sense, symbolic notation functions as a relational and heuristic tool, aimed at reducing conceptual ambiguity and facilitating comparison across technological systems, rather than replacing empirical description or detailed technological analysis [6,7,39,66].

Within this framework, a technological principle is not defined solely by recurrent empirical observation, but by the explicit formulation of necessary relationships between conditions, operations, and outcomes. Symbolic notation is therefore not an optional stylistic device, but a methodological requirement: without an explicit relational formulation, a

proposed “principle” remains at the level of descriptive regularity rather than constituting a law-like statement in a strict sense.

Basic conventions of relational and logical symbolism (e.g., implication arrows, conjunction and composition operators) follow standard usage in logic and philosophy of science, as outlined in classic introductions to logic and in widely used reference works [66,67]. Symbols are used here in a minimalist and declarative sense, with all operators explicitly defined in each case to avoid ambiguity or implicit formal assumptions. In particular, the operator $\oplus$ is used to denote the physical interaction (application of energy) between the agent and the material, while the arrow $\rightarrow$ represents the transformation operator (technical process) leading to a specific morphological state

On this procedurally grounded basis, the following inventory presents a first operational formulation of legaliform principles in lithic technology, illustrating how they can be explicitly stated and applied to concrete technological cases.

The following principles describe the necessary relationships between technical actions and their morphological outcomes. However, a fundamental distinction must be made regarding the physical nature of the raw materials involved. While flaked technology (Principles 1, 2, and 3) is governed by the mechanics of brittle fracture and the propagation of conchoidal waves, the Principle of Ground Stone (P_{GS}) operates under different physical constraints. In the latter, technical transformation is not driven by the removal of clasts but by iterative mechanical abrasion, pecking, and grinding. Consequently, the legaliform constraints for Ground Stone are governed by friction and compressive stress rather than the controlled propagation of Hertzian cones. Consequently, the physical interaction ($\oplus$) in the Principle of Ground Stone (P_{GS}) must be understood as the application of abrasive or compressive force (A_{br}) rather than conchoidal percussion ($P(C)$).

A crucial clarification must be made regarding raw material constraints. Stoneworkers across the globe utilize materials with highly divergent isotropic and mechanical properties, ranging from highly homogenous obsidian and fine-grained cherts to granular quartzites and coarse silcretes. These material differences directly dictate the specific cultural recipes, force applications, and tool selection within a given *chaîne opératoire* [36,68]. However, from a techno-scientific perspective, the underlying mechanics of brittle fracture and the propagation of conchoidal waves remain physically invariant across all these high-silica stones [20,21,69–71]. The legaliform principles described below act precisely as nomoprismatic boundary conditions: they define the essential mechanical relationships (e.g., the coordination of angle, platform, and energy) that must be satisfied to achieve technical adequacy, regardless of the specific rock type. Thus, raw material variation determines the localized threshold of difficulty and adjustment, but it does not alter the universal structure of the legaliform operators themselves.

4.1. Bifacial Reduction Principle

Bifacial reduction constitutes one of the most pervasive legaliform principles in lithic technology. Its repeated application leads reliably to the production of artifacts with biconvex longitudinal and transverse sections, regardless of raw material type, percussion technique, or specific stage within the reduction sequence.

Symbolic notation

PBR: $(V_i \oplus A_{alt}) \rightarrow S_{bi}$

Where

PBR = bifacial reduction principle.

V_i = initial knappable volume.

A_{alt} = alternating removals on opposed faces.

S_{bi} = biconvex sectional geometry.

Descriptive notation

The systematic application of alternating removals on opposed faces to an initial knappable volume necessarily generates biconvex longitudinal and transverse sections, regardless of final tool outline.

Interpretation

From a cognitive perspective, the consistent enactment of bifacial reduction relies on procedurally learned patterns of action, rather than on formally articulated planning or abstract volumetric reasoning. The legaliform character of this principle lies in the necessary relationship between procedure and outcome: whenever removals are alternated between two faces within minimal angular constraints, a biconvex morphology emerges. This result does not depend on exhaustive planning, explicit volumetric calculation, or the anticipation of a final ideal form. It is a direct consequence of the mechanical behavior of conchoidal fracture under alternating extractions.

From the perspective of bounded rationality, bifacial reduction operates as a satisficing mechanism. It produces supports that are sufficiently robust, versatile, and maintainable for a wide range of tasks, without maximizing any specific functional or economic variable. Its long-term persistence across time and space reflects general technical adequacy rather than context-specific adaptation.

In terms of data verification, the PBR formula acts as a diagnostic tool: if biconvexity is observed, the underlying alternating removal process can be inferred with high reliability, providing a stable criterion for technological auditing.

While bifacial reduction provides a general solution for structuring volumetric supports through alternating removals, other legaliform principles operate through different procedural logics. One of the most widespread of these involves the systematic concentration of removals on a single face, giving rise to stable volumetric configurations through extended unifacial action.

4.2. Extended Unifacial Reduction Principle

Extended unifacial reduction represents a fundamental legaliform principle widely documented in the manufacture of unifacial tools such as scrapers, limaces, and related forms. Its repeated application leads to the progressive regularization of support thickness and the establishment of a stable plano-convex volumetric configuration, regardless of the final outline of the tool.

Symbolic notation

$$P_{UX}: (V_i \oplus A_{ext}) \rightarrow S_{pc}$$

Where

P_{UX} = extended unifacial reduction.

V_i = Initial knappable volumen.

$\oplus$ = Physical interaction operator (application of energy).

A_{ext} = Active face subjected to recurrent/invasive removals.

S_{pc} = plano-convex section.

Descriptive notation

Repeated and extensive removals from a single face of a lithic support progressively regularize thickness and generate a stable plano-convex sectional geometry prior to final edge shaping.

Interpretation

The legaliform character of extended unifacial reduction lies in the necessary relationship between procedure and volumetric outcome. Whenever removals are systematically concentrated on a single face, within workable angular conditions, thickness becomes progressively homogenized and a plano-convex configuration emerges. As in the case of

bifacial reduction, the recurrent activation of this principle relies on procedural memory acquired through practice rather than on explicit planning or abstract volumetric reasoning.

This principle does not reside in the final tool morphology, nor in the presence of marginal retouch alone, but in the extended and recurrent nature of removals that substantially modify the support's volume. It therefore precedes, and enables, later phases of edge regularization and maintenance. From the perspective of bounded rationality, extended unifacial reduction operates as a satisficing mechanism. It does not aim to optimize edge durability, raw material economy, or task-specific performance. Instead, it produces a sufficiently stable and maintainable volumetric configuration applicable across diverse materials and contexts. Its persistence reflects general technical adequacy rather than adaptation to particular environments or functional demands.

Whereas bifacial and extended unifacial reduction principles structure volumetric supports through recurrent patterns of removal, other legaliform principles operate by reorganizing the geometry of cores themselves in order to constrain and stabilize the production of blanks.

4.3. Prepared Core Principle

The preparation of cores introduces a higher level of technical structuring in lithic production. Through the partial or complete modification of core geometry—by establishing striking platforms, convexities, and preferential directions of removal—the variability of products is reduced and the predictability of blanks is increased.

Symbolic notation

$$P_{PC}: (V_i \oplus P_{(C)}) \rightarrow P_{UX}$$

Where

P_{PC} = prepared core principle.

V_i = Initial knappable volumen.

$\oplus$ = Physical interaction operator (application of energy).

$\rightarrow$ = Transformation operator (technical process).

ΣF_u = series of flakes with relatively uniform thickness.

Descriptive notation

The prior structuring of a core's geometry enables the recurrent extraction of blanks with constrained variability in thickness and general morphology.

Interpretation

The legaliform character of this principle resides in the necessary relationship between volumetric preparation and increased regularity of products. Importantly, preparation does not require a fully standardized or exhaustively prepared core; partial preparation or the use of naturally suitable surfaces may suffice to activate the principle.

From the perspective of bounded rationality, the preparation of cores operates as a satisficing mechanism that reduces future decisional complexity. Once appropriate volumetric conditions are stabilized, extraction sequences can proceed in a more automated and less cognitively demanding manner.

This principle enables forms of local maximization, particularly regarding raw material exploitation and product predictability. However, such maximization is always conditional and emergent. It becomes possible only after the technical problem has been simplified through prior satisficing procedures, and therefore does not constitute the guiding logic of lithic production.

While the preparation of cores aims at stabilizing volumetric conditions to increase the predictability of flake production, a further step in technical structuring is reached when extraction becomes strongly directional and oriented toward the systematic production of elongated blanks. In this context, blade production can be understood not as a distinct

technological “strategy,” but as the activation of an additional legaliform principle based on directional control and convexity maintenance.

4.4. Blade Production Principle

Systematic blade production constitutes a legaliform principle grounded in the control of extraction direction and the maintenance of a suitable longitudinal geometry guiding fracture propagation. This principle may operate on fully prepared, partially prepared, or minimally structured cores, including those initiated from natural ridges or suitable morphologies.

Symbolic notation

$$P_{BL}: (V_i \oplus M_{CR}) \rightarrow \Sigma B_{pf}$$

Where

P_{BL} = blade production principle.

V_i = Initial volume (A specially selected core or nodule).

$\oplus$ = Physical interaction operator (application of energy).

M_{CR} = *Maintenance and Core Reduction* (Specific technical actions for platform and longitudinal guide maintenance, such as cresting or striking platform rejuvenation).

$\rightarrow$ = *Transformation operator* (Technical process).

ΣB_{pf} = *Sum of Blade-like/Prismatic Forms* (The resulting series of standardized blades or laminar products).

Descriptive notation

Directional control of removals through volumetric organization of the core allows the recurrent production of elongated blanks with partially predetermined proportions.

Interpretation

The legaliform character of blade production lies in the stabilization of preferential fracture-propagation directions, regardless of whether the resulting products display convex, straight, or near-parallel longitudinal profiles. Once appropriate volumetric conditions are established, extraction can proceed in a relatively automated manner until these conditions are exhausted.

As in the case of prepared cores, blade production allows for clear forms of local maximization, particularly in terms of raw material efficiency and product standardization. However, this maximization is conditional and derivative, not foundational. It emerges only after the volumetric problem has been simplified through satisficing procedures that stabilize the core’s geometry.

From a bounded rationality perspective, blade production does not presuppose exhaustive planning or the anticipation of an entire reduction sequence. Rather, it operates through the progressive activation of a robust legaliform principle that reliably generates elongated products under a wide range of material and contextual conditions.

These principles and their associated symbolic formulations are intended to be mobilized within empirical archaeological analyses, allowing technological interpretation to move beyond purely descriptive accounts and toward the explicit articulation of necessary technical relationships, without invoking optimizationist or normativist assumptions.

4.5. Bipolar Reduction Principle

Bipolar reduction constitutes a legaliform principle activated under conditions of severe volumetric constraint, limited blank size, or poor knappability. By placing a core or blank on an anvil and applying force from above, fracture is initiated and propagated simultaneously from opposed points of impact, producing characteristic axial compression and bidirectional scar patterns.

Symbolic notation

$$P_{BP}: (V_i \oplus C_{ax}) \rightarrow \Sigma F_{bi}$$

Where

P_{BP} = bipolar reduction principle.

V_i = *Core Volume* (Usually a small nodule, pebble, or exhausted core).

$\oplus$ = *Physical interaction operator* (Application of energy through a percussion-on-anvil setup).

$\rightarrow$ = *Transformation operator* (Technical process).

ΣF_{bi} = *Sum of Bipolar Forms* (Set of splintered pieces, scaled flakes, or “pièces esquillées” with bipolar characteristics).

Descriptive notation

The application of axial compression to a constrained lithic volume necessarily generates bidirectional fractures and flake fragments, regardless of raw material quality or blank morphology.

Interpretation

The legaliform character of bipolar reduction lies in the necessary relationship between axial compression and bidirectional fracture propagation. Once a volume is constrained between two opposed impact points, fracture initiation and termination are mechanically structured by this configuration, producing recurrent morphological and scar patterns.

From the perspective of bounded rationality, bipolar reduction operates as an extreme satisficing mechanism. It enables continued production when other reduction principles are no longer viable, prioritizing immediate usability over control, predictability, and morphological regularity.

4.6. Maintenance and Solutions Principle

Maintenance and reactivation constitute a legaliform principle governing the prolongation of tool use-life through localized removals aimed at restoring functional edges or volumetric balance. This principle operates independently of initial production strategy and may be repeatedly activated throughout an artifact’s history.

Symbolic notation

$$P_{MR}: (T_u \oplus D_f) \rightarrow F_r$$

Where

P_{MR} = maintenance and reactivation principle.

T_u = *Used or exhausted tool* (An artifact showing edge dulling or functional failure).

$\oplus$ = *Physical interaction operator* (Application of mechanical energy).

D_f = *Differentiated Flaking* (Specific technical actions of retouching or edge rejuvenation).

$\rightarrow$ = *Transformation operator* (The technical process of restoration).

F_r = *Functional Restoration* (The state of recovered utility or morphological adequacy).

Descriptive notation

Localized removals applied to a used tool necessarily modify edge configuration and overall morphology in order to restore functional adequacy.

Interpretation

In this context, reactivation is not equivalent to resharpening in a normative or formal sense. Rather than aiming to restore an original or idealized tool form, reactivation refers to localized technical interventions that restore functional adequacy under changing volumetric and edge conditions. These interventions may result in significant morphological modification or divergence over time, reflecting satisficing responses to use-related degradation rather than adherence to predetermined design templates.

The legaliform character of maintenance and reactivation lies in the necessary relationship between functional degradation and localized volumetric or edge modification.

This principle explains recurrent patterns of reshaping, reduction, and morphological divergence observed in archaeological assemblages.

From a bounded rationality perspective, maintenance and reactivation represent satisficing responses to functional decline, privileging continuity of use over replacement or redesign.

This principle is critical for standardizing the study of artifact life-histories, as it explains morphological divergence as a predictable outcome of maintenance rather than as “stylistic drift.”

4.7. Thermal Alteration Principle (P_{TT})

Acts as a techno-scientific bridge by modifying the internal structure of the rock to increase predictability.

Symbolic notation: $P_{TT}: (V_i \oplus \Delta T) \rightarrow \Delta K$

Where

P_{TT} = Thermal alteration principle.

V_i = Initial Volume (Raw material in its natural state, such as chert, flint, or chalcedony).

$\oplus$ = Physical interaction operator (Application of controlled heat).

ΔT = Thermal Gradient (Controlled increase and cooling of temperature within a specific range).

$\rightarrow$ = Transformation operator (Technical process).

ΔK = Mechanical Change/Fracture Improvement (Transformation of the rock's crystallinity, increasing its flaking quality and reducing fracture toughness).

Interpretation: Controlled heating (ΔT) reduces fracture toughness (ΔK). It is a nomo-pragmatic requirement for some bifacial thinning and certain high-precision pressure flaking tasks. From a materials science perspective, this is a clear instance of material standardization initiated by prehistoric agents to ensure the reproducibility of subsequent flaking results.

4.8. Ground Stone Principle (P_{GS})

Based on progressive material removal through mechanical attrition (pecking) and friction (abrasion).

Symbolic notation: $P_{GS}: (V_i \oplus Aabr) \rightarrow Ssm$

Where

P_{GS} = Ground stone principle.

V_i = Initial lithic volume (Non-conchoidal or tough rocks).

$\oplus$ = Physical interaction (Application of compressive or frictional energy).

$Aabr$ = Action of mechanical attrition (pecking) and abrasion (friction).

$\rightarrow$ = Transformation operator (Technical process).

Ssm = Smoothed or regularized surface geometry.

Interpretation: Continuous abrasive friction ($Aabr$) leads to the regularization and smoothing (Ssm) of the surface. It involves a distinct sensorimotor coordination (rhythmic friction vs. impulsive impact).

For analytical clarity, Table 2 provides a synthetic overview of the legaliform principles discussed above. This summary is intended as a heuristic device to highlight the core procedural logic, technical outcomes, and bounded rationality functions associated with each principle, without implying discrete technological strategies, exhaustive descriptions, or direct correspondence with empirical assemblages.

Table 2. Formalized Inventory of Legaliform Principles: Procedural Logic, Symbolic Notation, and Material Constraints.

Principle	Symbolic Notation	Physical Basis	Cognitive/Procedural Logic	Technological Outcome
Bifacial (P _{BR})	$(V_i \oplus A_{alt}) \rightarrow S_{bi}$	Brittle fracture (Conchoidal)	Alternating removals/Procedural symmetry	Biconvex sectional geometry
Extended Unifacial (P _{UX})	$(V_i \oplus A_{ext}) \rightarrow S_{pc}$	Brittle fracture (Conchoidal)	Recurrent single-face removals	Plano-convex sectional geometry
Prepared Core (PPC)	$(V_i \oplus P(c)) \rightarrow \Sigma Fu$	Controlled fracture mechanics	Volumetric stabilization/Satisficing	Uniform flakes/Constrained variability
Blade Production (P _{BL})	$(V_i \oplus M_{CR}) \rightarrow \Sigma B_{pf}$	Directional fracture propagation	Longitudinal guide maintenance	Elongated/Prismatic blanks
Bipolar (P _{BP})	$(V_c \oplus C_{ax}) \rightarrow \Sigma F_{bi}$	Axial compression (Anvil)	Extreme satisficing/Force-driven	Splintered pieces/Bidirectional scars
Maintenance (P _{MR})	$(T_u \oplus D_f) \rightarrow F_r$	Localized fracture/retouch	Functional sufficiency/Curative	Restored edge/Morphological divergence
Thermal Alteration (P _{TT})	$(V_i \oplus \Delta T) \rightarrow \Delta K$	Material thermodynamics	Nomopragmatic preparation	Improved knappability/Predictability
Ground Stone (P _{GS})	$(V_i \oplus A_{abr}) \rightarrow S_{sm}$	Mechanical attrition & friction	Rhythmic sensorimotor coordination	Smoothed or regularized surfaces

The inventory of legaliform principles outlined above provides a conceptual framework for understanding the recurrent technical regularities underlying lithic production. In the following section, we illustrate how these principles are mobilized in practice through an empirical example: the manufacture and maintenance of Fell points. This case demonstrates the sequential, overlapping, and context-dependent activation of multiple principles, highlighting the role of procedural memory and satisficing strategies in shaping artifact morphology over time.

5. Summary of the Framework

Table 2 summarize the legaliform principles presented in this section, providing a concise reference for their procedural logic, technical outcomes, and cognitive functions. This hierarchical structure is designed to align with international frameworks for data categorization and scientific auditing.

6. Case Study: Fell Projectile Points and the Operationalization of Legaliform Principles

The Paleoindian Fell points (also known as “Fishtail” points) of South America provide an ideal case study for our model. Their wide geographic distribution and morphological variability have historically sparked debates over whether they represent rigid “mental templates” or highly plastic, functional tools [54,55]. Our framework suggests that the stability of the “type” is a product of legaliform necessity (Techno-science), while its variability is a product of bounded rationality and maintenance.

From the perspective of data standardization and technical verification, this case study serves as a validation protocol. For a robust testing of an analytical framework, its application to a highly variable, real-world population is required to demonstrate that the proposed metrics can absorb empirical variance without losing explanatory power

6.1. The Structural Base: Activation of P_{BR} and P_{TT}

The production of a Fell point consistently activates the Bifacial Reduction Principle (P_{BR}):

$$\text{Formula: } P_{BR}: (V_i \oplus A_{alt}) \rightarrow S_{bi}$$

This principle ensures a biconvex, balanced volume (S_{bi}) essential for ballistic performance. Furthermore, in many regional contexts, the reduction sequence may incorporate the Thermal Alteration Principle (P_{TT}) as an optional but critical technological choice. Rather than a fixed initial stage, P_{TT} acts as a nomoprismatic bridge that can be activated when high-silica materials require a modification in fracture toughness (ΔK) to enable high-precision pressure flaking.

6.2. Life-History Variability and the Maintenance Principle (P_{MR})

The observed variability in blade length, width, and symmetry in Fell points is easily understood through the activation of the Maintenance and Reactivation Principle (P_{MR}):

$$P_{MR}: (T_u + D_f) \rightarrow F_r$$

When a projectile point suffers functional degradation (D_f)—such as a fractured tip or edge dulling through use—the knapper applies a satisficing solution: localized removals (F_r) aimed at restoring functional restoration.

This legaliform response explains why resharpened Fell points often appear “stubby,” asymmetrical, or significantly reduced in length compared to pristine specimens. Within our framework, these are not “failed” versions of an ideal template, nor do they represent distinct “sub-types”; they are technically adequate states maintained through P_{MR} under conditions of bounded rationality. The morphological “norm” is thus a moving target, structured by the interaction between the stable requirements of the P_{BR} principle and the recurrent, opportunistic activation of maintenance procedures (see Figure 1).

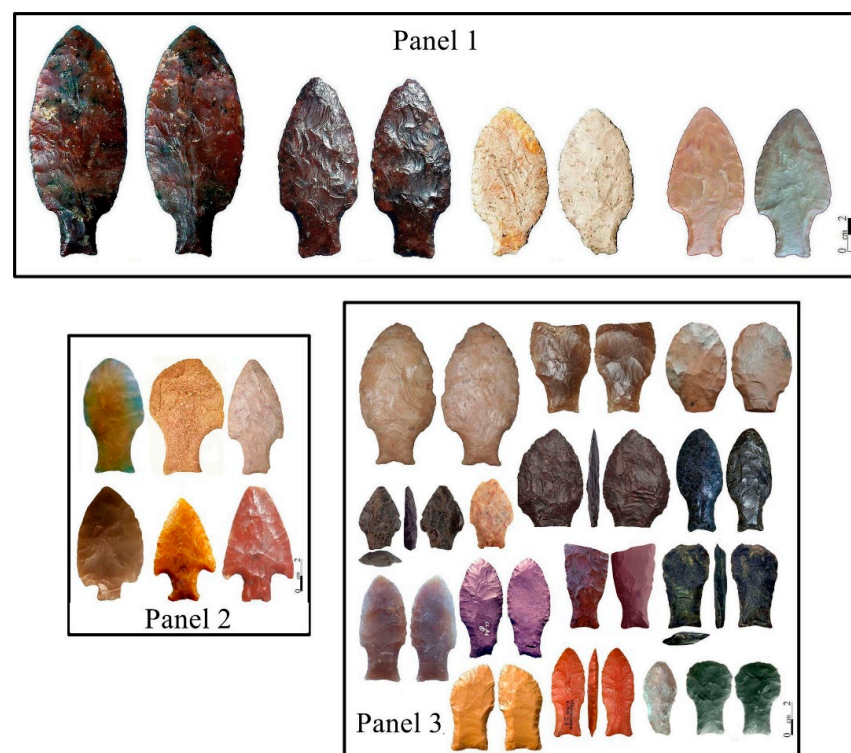


Figure 1. The Operationalization of Legaliform Principles in Fell (Fishtail) Projectile Points. The figure illustrates how physical principles (nomopraxisms), techno-scientific necessity, and bounded

rationality converge to create the observed morphological variability. Panel 1: Pristine and early-stage Fell points demonstrating the activation of the Bifacial Reduction Principle (P_{BR}) and Pressure Flaking Principle (P_{PF}) to achieve optimal biconvexity (S_{bi}), structural integrity, and ballistic symmetry. Panels 2 and 3: Archaeological specimens exhibiting diverse ‘life-history’ states. The pronounced reductions in length, tip rejuvenation flakes, ‘stubby’ morphologies, and asymmetrical edges are the emergent result of the recurring and opportunistic activation of the Maintenance and Reactivation Principle (P_{MR}). This variability represents culturally appropriate and technically adequate states—satisficing solutions—rather than failures to meet a rigid ‘mental template’.

By focusing on these legaliform principles, we move beyond the descriptive trap of morphological “types” and begin to understand the life-history of Paleoindian technology as a series of procedurally grounded responses to universal physical and functional problems. Consequently, the classification of these artifacts shifts from an intuitive, subjective typology to a standardized, reproducible audit of technological performance over time.

7. Discussion: Guided Convergence and the Structural Logic of Lithic Technology

The legaliform framework does not seek to replace the *chaîne opératoire*. Instead, it provides the missing intermediate analytical level that explains why certain technological patterns recur globally. As noted by Mark Moore [72,73], complex forms can emerge from simple algorithms. This is particularly relevant for understanding the long-term technological stasis and subsequent transitions observed in the prehistoric Paleolithic record, where traditional Western typologies often fail to capture the underlying technical logic. While Moore emphasizes emergent “spandrels,” the legaliform perspective highlights the agency of the knapper in activating these techno-scientific relationships to solve technical problems under conditions of bounded rationality.

7.1. Resolving the “Finished Product” Debate

By utilizing the PMR principle, we formally demonstrate that a stone tool is not a “failed” attempt at a mental template, but a sequence of technically adequate states. This addresses the “Finished Product Fallacy” [18] by providing a mathematical notation for maintenance as a structural part of the technology, rather than an accidental byproduct. Under this framework, the artifact is defined as a “dynamic equilibrium” between functional degradation (D_f) and the restoration of technical adequacy (F_r). Each modification in the reduction sequence represents a necessary response to maintain the viability of the lithic system, moving the focus from static typological “ideals” to the objective reality of technical trajectories.

7.2. Guided Convergence vs. Cultural Tradition

The distinction between legaliform principles and cultural recipes is crucial. While the specific choice of a “fishtail” base in South America is a product of information transmission (social learning), the internal biconvexity of the point is a result of Guided Convergence [74]. Any knapper seeking a thin, maintainable bifacial tool will be “guided” by PBR toward the same biconvex solution.

Historically, macroscopic similarities between early American projectile points and Old World toolkits have occasionally led to diffusionist interpretations that presuppose direct cultural contact or migration events based primarily on shared forms (e.g., [75–77]). Alternatively, contemporary debates frequently focus on highly specific cultural transmissions or idealized mental templates to explain technological stasis. While social learning and traditional transmission are undeniably central to the maintenance of historical styles—such as the specific choice of a ‘fishtail’ base morphology—the structural biconvexity of the

point is more parsimoniously explained through Guided Convergence [74]. Any knapper attempting to produce a thin, reliable, and maintainable bifacial tool is inherently constrained by the laws of conchoidal fracture. By identifying universal legaliform principles, archaeology can explain morphological convergences across distant regions not as historical anomalies or direct transmissions, but as independent, technically adequate solutions to shared physical problems. This framework allows regional records to be integrated into global comparative baselines without imposing external historical trajectories or relying exclusively on intuitive typological matches.

7.3. Epistemological Boundaries and the Avoidance of Empty Formalism

While formal notational systems are powerful tools for structural clarity, they are not immune to epistemological pitfalls. The primary risk of utilizing an algebra-like notation in archaeology is the trap of ‘empty formalism’ or nominalism—namely, the hazard of translating mundane descriptive categories into complex symbols without adding genuine explanatory value, or worse, creating a rigid system that misleads the researcher by oversimplifying human agency.

We actively avoid these pitfalls through three methodological safeguards. First, our algebraic symbols do not represent arbitrary cultural labels; instead, every operator is strictly anchored to the physical and invariant laws of conchoidal fracture and elastomechanics [20]. Second, the equations are designed as open state-space models under bounded rationality [7]. They do not predict a single, deterministic ‘optimum’ path, but rather define the broad boundary conditions within which ‘satisficing’ (adequate) technical choices are possible. Lastly, the model’s validity is continuously cross-referenced and constrained by experimental archaeology and replicative knapping. By ensuring that every symbolic transformation in the algebra corresponds to a physical, experimentally verified gesture, the framework remains a grounded, pragmatic tool for analysis rather than an abstract mathematical exercise.

8. Conclusions

This article has introduced a formal framework for identifying and notating legaliform principles in lithic technology. By grounding these principles in Mario Bunge’s socio-natural science, Herbert Simon’s theory of bounded rationality, and the techno-scientific foundations of Schiffer and Skibo, we provide a robust epistemological basis for interpreting the archaeological record.

The primary advantages of this framework are:

- **Comparability:** The standardized notation developed here ($\oplus$, $\rightarrow$, Σ) allows for the rigorous comparison of lithic assemblages across disparate regions and time periods using a universal “technical algebra.” This directly satisfies strict scientific requirements for reproducibility and cross-laboratory data alignment.
- **Explanatory Power:** It accounts for both technological stability (principles) and morphological variability (maintenance and satisficing behavior) without resorting to normative templates or idealized mental models.
- **Integration:** It bridges the gap between the physics of brittle fracture and the cognitive, embodied aspects of human technical action, positioning the knapper as an active problem-solver.

The adoption of this legaliform framework is especially vital for the current expansion of archaeological research globally. As the discipline increasingly moves away from Eurocentric benchmarks, there is an urgent need for “trans-regional” methodologies that allow for a direct, scientific comparison across Asian, African, Oceanian, and American lithic records. The formalized algebra presented here offers a path toward a non-colonial,

globally calibrated framework for archaeological data curation, technical reporting, and cross-continental comparison.

Recognizing these legaliform principles allows archaeology to move beyond descriptive typology toward a more predictive and explanatory science of human technical behavior. It acknowledges the knapper not as a passive copier of forms, but as a situated agent managing the universal laws of matter. In this sense, this framework serves as an essential tool for documenting the diverse histories of human innovation while acknowledging the immutable physical laws that govern stone tool production.

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