Computative Economics

A Framework for Economic Analysis under Computational Abundance

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Abstract

This paper develops Computative Economics as a framework for economic analysis where the binding constraint on production is computational rather than physical. The framework generalizes Arrow-Debreu equilibrium existence to economies with endogenous possibility spaces. Homo economicus is replaced by the computative agent, a tuple (C, O, M, G, R); the scarce good by the generated possibility space; competitive equilibrium by recursive equilibrium, formalized as the fixed point of a composite best-response map. Existence is proved via Brouwer under convexity and continuity; uniqueness and convergent iteration via Banach under contraction. Four propositions are derived from fourteen stated assumptions, and Ostrom's design principles for commons governance are translated to the computational domain. The framework is positioned as a companion paradigm to Neoclassical Economics, applicable where the computational primitive holds.

Keywords: computative agent; generated possibility space; recursive equilibrium; Brouwer fixed-point theorem; Banach fixed-point theorem; commons governance; computational abundance; objective function governance

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I. Introduction

This paper generalizes the existence of competitive equilibrium (Arrow and Debreu 1954) to economies in which the set of producible outputs is not exogenously given but is generated by agents whose binding constraint is computational. The Arrow-Debreu formalization rests on a fixed commodity space over which excess demand is defined and to which fixed-point theorems are applied. The framework developed here replaces this structure with a best-response map on the product space of generation functions and domain models, establishes existence via Brouwer under continuity and convexity conditions, and establishes uniqueness together with convergent iteration via Banach under an additional contraction condition.

The substantive motivation is the shift in the production function of information-intensive goods from a physical-scarcity regime to a regime in which the marginal cost of an additional realization approaches zero while the binding constraint relocates to the computational infrastructure that generates realizations. The formal consequence is that the commodity space on which the classical existence theorem operates becomes endogenous to agents' generative activity. The classical existence theorem does not extend mechanically to this setting. The generalization developed here is mathematically direct in structure but substantively significant: it produces a different equilibrium object (a profile of generation functions rather than a price vector and allocation), different coordinating signals (a composite of price, reputation, and verified generative capacity rather than price alone), and a different locus for opportunity cost (foregone generative capacity rather than foregone realizations).

The paper sits in the tradition of paradigm-founding reconstitutions in economic theory. Each major shift has proceeded by changing the foundational primitive rather than by refining existing machinery applied to new phenomena. The classical framework took the distribution of social product among land, labor, and capital as its primitive; the neoclassical framework took choice under scarcity (Robbins 1932) as its primitive; general equilibrium theory formalized the neoclassical primitive and established the conditions under which it delivers coherent aggregate results (Arrow and Debreu 1954; Debreu 1959). The New Institutional Economics extended the framework by showing that the institutional structure of the economy emerges endogenously from transaction costs, bounded rationality, and information asymmetry (Coase 1937; Simon 1955; Akerlof 1970; Williamson 1985; North 1990), retaining the scarcity primitive throughout. The present paper proposes the primitive of a computative agent whose binding constraint is computational, and constructs the apparatus that primitive requires.[2]

The scope of the generalization is specified rather than universal. Neoclassical Economics remains the appropriate framework for the domain in which the scarcity primitive holds, which continues to cover the production of physical goods whose marginal cost remains bounded above zero. The computative framework applies to the domain in which generative activity by computative agents produces outputs whose realization-level marginal cost approaches zero while the binding constraint relocates to computational capacity. The boundary between the two domains is an object of empirical investigation. The two frameworks coexist in analogy to the coexistence of classical and neoclassical frameworks in the decades following the marginalist formulation.

The remainder of the paper is organized as follows. Part II establishes the primitives of Computative Economics and states the primitive contrasts with Neoclassical Economics in Table 1. Part III develops the computative agent formally, specifying its tuple representation (C, O, M, G, R) and its decision problem. Part IV develops the generated possibility space as the unit of analysis and characterizes its quality metrics. Part V identifies three cross-cutting mechanisms through which the scarcity primitive ceases to govern the production functions of information-intensive goods. Part VI develops recursive equilibrium as the coordinating concept and proves existence and convergence via the Brouwer and Banach fixed-point theorems; the structure of the argument is depicted in Figure 1. Part VII states four propositions. Part VIII states the

[2] The argument that the load-bearing assumptions of scarcity-based economic theory (scarcity of intelligence, bounded rationality, information asymmetry, positive transaction costs, and temporal latency in price discovery) dissolve simultaneously as computational abundance becomes the operative condition of value creation is developed in Kaal (2026a). The present paper takes that argument as given and constructs the successor framework rather than relitigating the destructive argument.

model assumptions formally. Part IX develops governance infrastructure, including the translation of Ostrom's (1990) design principles for commons governance to the computational domain. Part X distinguishes Computative Economics from adjacent frameworks. Part XI sets out open problems. Part XII concludes.

II. The Primitives of Computative Economics

Every economic theory rests on a set of primitives that are not themselves derived from within the theory but are taken as the starting points from which derivation proceeds. The primitives determine what phenomena the theory can analyze, what questions it can ask, and what answers count as valid. Table 1 states the core primitive contrasts between Neoclassical Economics and Computative Economics that organize the remainder of the paper.

Table 1. Primitive Contrasts between Neoclassical and Computative Economics

Dimension	Neoclassical Economics	Computative Economics
Foundational axiom	Scarcity of means relative to ends (Robbins 1932)	Computational primitive: binding constraint is computational, not physical
Analytical primitive	Rational agent (homo economicus)	Computative agent, tuple (C, O, M, G, R)
Object of analysis	Scarce good with fixed attributes	Generated possibility space S = G(C, O, M)
Choice structure	Selection among fixed alternatives	Generation of alternatives followed by selection
Optimization	Maximization over given feasible set	Allocation of resources across generation and refinement
Equilibrium concept	Competitive equilibrium (Arrow and Debreu 1954)	Recursive equilibrium: fixed point of composite best-response map Ψ
Coordinating signal	Price	Composite of price, reputation, and verified generative capacity
Opportunity cost locus	Next-best foregone alternative	Foregone allocation of generative capacity
Competition locus	Output price and quantity	Quality of generative capacity
Distribution axis	Factor endowments and marginal productivity	Access to computational infrastructure
Policy instruments	Price and quantity controls; monetary and fiscal policy	Computational access governance; objective function governance

Notes: The first column identifies an analytical dimension; the second and third columns state the corresponding primitive or construct under each framework. Parts III through IX develop each row.

A. From Rational Agent to Computative Agent

The Neoclassical agent is defined by preferences over a fixed set of alternatives and a budget constraint that limits which alternatives are attainable. The agent's problem is to select, from the feasible subset of the alternative set, the alternative that maximizes utility. The bounded-rationality correction (Simon 1955) modified this agent by limiting its cognitive capacity but preserved the structure of the problem: a fixed alternative set, a budget or cognitive constraint, and an optimization rule operating on a given domain.[3] The computative agent differs from both the Neoclassical and the bounded-rationality agent in three structural respects.

First, the alternative set is not fixed. The computative agent generates its alternatives through computation. Given computational resources, an objective function, and a model of the relevant domain, the agent produces candidate alternatives through generation, refinement, and recombination. The alternative set is therefore endogenous to the agent's activity rather than exogenously given. Second, the binding constraint is computational rather than physical. The Neoclassical budget constraint limits the agent by the price of goods and the wealth available to purchase them. The computative agent's constraint is the computational infrastructure available to generate, evaluate, and execute alternatives. This infrastructure comprises processing capacity, training data, model architecture, memory, and energy. Third, the agent's decision-making capacity is endogenous to its history of action. Every generation-evaluation-verification cycle updates the agent's internal model, which in turn modifies the generation function available in subsequent cycles. This endogeneity has no analog in the Neoclassical agent, whose preferences and choice rules are fixed.

B. From Scarce Good to Generated Possibility Space

The Neoclassical good is a discrete bundle of attributes that can be produced, exchanged, and consumed. Its price reflects the marginal rate of substitution between it

[3] On the stability of preferences as a methodological commitment of neoclassical theory, see Becker and Stigler (1977).

and other goods at equilibrium quantities. Its scarcity is what makes it an object of economic analysis at all. In the formulation of Robbins (1932), a good is economic only insofar as its abundance falls short of the ends to which it might be applied. The computative good is not a discrete bundle. It is a region of possibility space. A legal analysis generated by a computative system is not a single document whose value is set by scarcity. It is one realization drawn from a distribution over possible analyses the system could have generated given the same inputs. The value of what the system produces derives not from the scarcity of the specific realization but from the quality of the underlying distribution from which realizations are drawn. The economic object is therefore the possibility space itself, not the particular realization.

This is a significant departure. Under Neoclassical assumptions, opportunity cost is the value of the next-best foregone alternative. The concept presupposes that alternatives are fixed and that choice is a matter of selecting among them. When alternatives are generated rather than given, opportunity cost changes its referent. The opportunity cost of producing a specific realization is not the next-best realization that could have been produced instead. It is the foregone quality of the generative capacity that would have been available if the computational resources had been allocated differently. Opportunity cost migrates from the good to the infrastructure that generates the good.

C. From Market to Generative Network

The Neoclassical market is a coordination mechanism in which buyers and sellers exchange given goods at prices determined by the intersection of supply and demand. Walras (1874) formalized this coordination through the tâtonnement process, in which a notional auctioneer announces prices and adjusts them until excess demand vanishes in every market simultaneously. The English-language tradition inherited the Walrasian framework primarily through the Arrow-Debreu formalization (Arrow and Debreu 1954; Debreu 1959). The Neoclassical market presupposes that the set of goods is fixed, that preferences are fixed, that information is either complete or its asymmetries are well-characterized, and that the tâtonnement process converges in time scales that are economically meaningful.

The computative counterpart is the generative network. In a generative network, agents do not exchange pre-specified goods at given prices. They exchange generated outputs whose specifications are themselves produced through the interaction. The coordination signal is not price alone. It is a composite of price, reputation, and verified generative capacity. A generative network converges not to a price vector that clears a market but to a configuration of generative capacities that no agent can improve upon given the configurations of others. Part VI formalizes this convergence concept as recursive equilibrium.

D. Agentic Decoupling and Terminal Consumption

Two further features of the computative setting require specification before the formal development proceeds. The first is the structural severance of value creation from human labor and consumption at the production-function level, which in what follows is referred to as agentic decoupling. Previous waves of automation accelerated human-directed activity within existing institutional frames. The computative setting is distinct in that autonomous agents generate, verify, and reinvest outputs among themselves, producing economic layers that operate without continuous human participation at each transaction node. The claim is not that human consumption disappears. It is that human consumption ceases to be the proximate driver of the dominant mode of production in the affected domain.

The second feature is the distinction between terminal and proximate consumption. In Neoclassical analysis, human consumption decisions drive production decisions at each margin. In the computative setting, humans remain the terminal consumers of value, but the vast majority of transactions in the production chain occur among agents. A computative system that designs, tests, and optimizes drug candidates through thousands of agent-to-agent transactions before a human patient benefits is serving terminal human consumption, but the proximate driver of each intermediate transaction is not a human consumption decision. The analytical consequence is that demand-side analyses that assume proximate-consumption structure lose descriptive accuracy in domains where the computative primitive holds. Welfare analysis in such domains must work at the terminal rather than proximate level.

III. The Computative Agent

This part develops the computative agent formally, specifies its decision problem, and distinguishes it from the Neoclassical and bounded-rationality agents.

A. Formal Specification

A computative agent is characterized by a tuple (C, O, M, G, R), where C denotes the agent's computational resources (a nonnegative real-valued vector representing processing capacity, memory, training data volume, model parameters, and available energy). O denotes the agent's objective function, mapping candidate outputs to a real-valued evaluation. M denotes the agent's domain model, a representation of the domain over which the agent operates, including both structural relationships and uncertainty. G denotes the agent's generation function, mapping (C, O, M) into a distribution over candidate outputs in the possibility space. R denotes the agent's reputation, a non-transferable scalar or vector tracking the agent's history of verified generative performance in its operating domain.

The agent's decision problem at decision epoch t is to choose an allocation a_t of computational resources across generation and refinement operations that maximizes the expected quality of the resulting possibility space, subject to the budget constraint that allocated resources cannot exceed C_t and subject to the requirement that the domain model M_t update after each generation-verification cycle on the basis of observed outcomes:

$$\max_{a_t \in A_t} \; E[\, Q(G(C_t, O, M_t; a_t)) \,] \quad \text{s.t.} \quad \Sigma\, a_t \leq C_t$$

where Q is a quality functional on the possibility space developed in Part IV.B. The distinction from the Neoclassical problem is that G operates on (C, O, M) to produce a distribution over outputs, rather than selecting a single output from a fixed menu. The agent does not choose among alternatives; it generates them, and the generation process is itself the object of optimization.

B. Distinction from Homo Economicus

Homo economicus is defined by a preference ordering over a fixed choice set, a budget constraint, and a selection rule that picks the preference-maximizing element of the feasible subset. The agent is static in the sense that the preference ordering does not change with the agent's experience of the choice set, and the choice set does not change with the agent's actions. The computative agent differs in three respects, each structural rather than parametric. The choice set is not fixed but generated, converting the selection problem into a subroutine within the generation problem. The objective function O, while analogous to Neoclassical preferences, operates on a qualitatively different argument: not a preference over goods that exist independently of the agent's activity, but an evaluation function over outputs the agent itself produces. And the generation function is endogenous to the agent's history through domain-model updating, a property absent from the Neoclassical agent.

C. Distinction from the Bounded-Rationality Agent

The bounded-rationality agent (Simon 1955) is sometimes proposed as an intermediate between homo economicus and any successor agent. Simon replaced the maximization rule with satisficing, in which the agent searches among alternatives until one meets an aspiration level and then stops. The satisficing rule responded to cognitive scarcity of the decision-maker. The computative agent is not a satisficer. Computational resources are capital rather than a fixed cognitive endowment. An increase in computational capacity increases the size and quality of the possibility space the agent can generate, which is a different kind of scaling than increasing the processing capacity of a fixed-preference maximizer. The computative agent continues to generate and refine until marginal generative quality falls below marginal computational cost, a stopping condition that differs in structure from the aspiration-level rule.

D. Reputation as Institutional Complement

Reputation R is the institutional complement to the generative capacity of the computative agent. In Neoclassical exchange, the quality of traded goods is either assumed known to both parties (the perfect-information case) or subject to institutional corrections such as warranties, signaling, and screening (Akerlof 1970; Spence 1973). In generative exchange, the good itself is a realization drawn from a generative distribution. The counterparty cannot evaluate the quality of the distribution from a single realization. The counterparty needs a track record: a verified history of the agent's generative outputs across prior interactions. Reputation serves this function, provided it is domain-specific and non-transferable. Domain specificity follows from the structure of generation, since an agent whose model is well-calibrated for one domain is not automatically well-calibrated for another. Non-transferability addresses the reputational analog of moral hazard, in which an agent accumulates reputation in one domain and then trades on it in another without commensurate generative competence.[4]

IV. The Generated Possibility Space

If the computative agent replaces homo economicus as the analytical primitive of the framework, the generated possibility space replaces the scarce good as its foundational object of analysis. This part develops the concept formally, specifies its quality metrics, and states its relation to adjacent concepts.

[4] The formal treatment is developed in Calcaterra, Kaal, and Rao (2018) and extended in Calcaterra and Kaal (2021) and Kaal (2026b).

A. Definition and Structure

The generated possibility space S_i of computative agent i is the image of the generation function G_i under the input (C_i, O_i, M_i):

$$S_i = G_i(C_i, O_i, M_i) = \{ y : y \text{ is feasible under } (C_i, O_i, M_i) \}$$

The space is not a fixed set of alternatives. It is constructed by the agent in the course of its operation. As any component of the input changes, so does the space. An increase in C_i expands the space. A refinement of M_i shifts the mass of the space toward higher-quality regions under Q. A change in O_i redirects the space toward a different region of the output domain. Three structural properties distinguish the generated possibility space from the Neoclassical commodity space. The space is agent-specific: two agents with different domain models will generate different possibility spaces even given identical computational resources and objective functions. The space is dynamic: it evolves with the agent's history of generation and verification. And the space is high-dimensional: the attributes of a generated output are as numerous as the features the generation function can distinguish.

B. Quality Metrics

Four functionals on the generated possibility space capture dimensions of its quality. Coverage measures the extent to which the space spans the domain of relevant outputs, formalized as the effective support of the generation distribution under a domain-specific measure. Precision measures the mass the generation function places on high-quality outputs, captured by the expected value of a draw from the generation distribution under O. Robustness measures the stability of the generation distribution under perturbation of the inputs. Calibration measures the alignment between the generation function's internal quality estimates and verified external performance. Value in Computative Economics derives from the composite of these dimensions rather than from any single one. This is the first proposition of the framework, stated in Part VII.

C. Opportunity Cost in a Generated Space

In Neoclassical Economics, opportunity cost is the value of the next-best alternative foregone. In a fixed alternative set, the concept is unambiguous. In a generated possibility space, the concept requires reformulation. Selecting a particular output from the space does not foreclose another specific output, because the alternative outputs were not pre-specified. What is foregone is not an alternative output but an alternative allocation of generative capacity. The opportunity cost of generating output y under resource allocation a is the expected quality of the output that would have been generated under an allocation a' that directed resources to a different region of the space. This reformulation has analytical consequences for the welfare theorems. The First Welfare Theorem requires a fixed production possibility frontier. When the frontier is endogenous to generative activity, Pareto optimality becomes path-dependent, and the theorem's existence proof fails. The welfare theorems remain valid within their original domain but do not extend to the computative domain.

D. Relation to Hayekian Knowledge

Hayek (1945) argued that the knowledge required for economic coordination is dispersed across agents and cannot be aggregated at a single point. Price, in Hayek's account, is the coordinating signal that conveys dispersed knowledge in a form agents can act on. The generated possibility space shares with Hayekian knowledge the property of being distributed across agents and resistant to aggregation, but it differs in two respects. Hayekian knowledge is knowledge of particular circumstances of time and place, held by individuals and communicated through their market activity. The generated possibility space is knowledge embodied in a generation function, held by a computative agent and communicated through the outputs the agent produces. Hayekian price operates as a summary statistic. The coordinating signal in Computative Economics is not a single scalar price but the composite of price, reputation, and verified generative capacity. Price alone is insufficient because it does not convey information about the quality of the generative distribution from which outputs are drawn. Reputation, which tracks verified generative performance, is the missing element.

V. Three Dissolution Mechanisms

The scarcity primitive ceases to govern the production functions of information-intensive goods through three cross-cutting mechanisms. The argument of the present paper does not depend on this part; the formal machinery developed in Parts III through VIII is self-contained. This part is included to specify the structural channels through which the computative primitive becomes operative, for readers who prefer to see the connection to the destructive argument developed in the companion paper (Kaal 2026a).

The first mechanism is marginal cost collapse. For any good whose production is information-intensive, the marginal cost of an additional realization approaches zero as generative infrastructure scales. This severs the price-cost relationship that underlies competitive market theory. When the thousandth realization of a legal analysis, a software module, or a financial model costs effectively nothing to produce, pricing based on scarcity of realizations loses its structural basis. The supply curve for realizations becomes horizontal at zero. Pricing in the computative domain attaches to generative capacity rather than to the realization.

The second mechanism is the transformation of information asymmetry. Classical market theory (Akerlof 1970; Spence 1973) relies on information asymmetry both as a source of inefficiency (generating adverse selection and moral hazard) and as a source of profit (generating arbitrage and expertise premia). The standard assumption is that information asymmetry arises from differential access to knowledge. Computational abundance does not eliminate information asymmetry, it transforms its locus. Traditional informational advantages, knowledge of market conditions, understanding of contract terms, possession of domain expertise, become accessible at negligible cost. New asymmetries emerge around proprietary models, training data quality, and computational infrastructure. The agent with superior compute generates a superior possibility space, and this computational advantage is not subject to the competitive dynamics that erode informational advantages in classical markets.

The third mechanism is cognitive labor substitution. The human capital tradition from Becker forward takes cognitive capacity as the scarce input that commands premium returns. As computative systems substitute for cognitive labor across expanding domains, the scarcity assumption on which wage theory rests fails across a widening frontier. The substitution is not merely quantitative. It is qualitative, producing outputs that human cognition cannot produce at equivalent cost, including real-time synthesis across large data volumes and simultaneous optimization across many variables. The three mechanisms compound. Marginal cost collapse undermines the price signals that information economics relies on. The transformation of information asymmetry relocates the binding informational constraint from knowledge possession to computational access. Cognitive labor substitution removes the human decision-makers whose bounded rationality justified the institutional structures that transaction cost economics analyzes.

VI. Recursive Equilibrium

Recursive equilibrium is the coordinating concept of Computative Economics. It generalizes competitive equilibrium (Arrow and Debreu 1954) and Nash equilibrium (Nash 1950) to the case in which agents generate their alternatives rather than selecting from a fixed alternative set. This part develops the concept formally, proves existence under specified conditions via the Brouwer fixed-point theorem, and proves uniqueness and convergent iteration under an additional contraction condition via the Banach fixed-point theorem. Figure 1 depicts the structure of the fixed-point argument.

A. Definition

Consider an economy with n computative agents. Each agent i has characteristics (C_i, O_i, M_i, G_i, R_i). Let G = (G_1, …, G_n) denote the profile of generation functions and M = (M_1, …, M_n) the profile of domain models. An allocation of computational resources across agents is $a = (a_1, \ldots, a_n)$, with $a_i \in A_i$. A recursive equilibrium is a profile of generation functions G^* and an allocation a^* such that two conditions hold simultaneously.

Condition 1 (Individual optimality). For each agent i, the allocation a_i^* maximizes the expected quality of the generated possibility space given the generation functions of the other agents G^*_{-i} and the domain model M_i:

$$a_i^* \in \arg\max_{a_i \in A_i} E[\, Q(G_i^*(C_i, O_i, M_i; a_i) \mid G^*_{-i}) \,]$$

Condition 2 (Model consistency). Each agent's domain model is consistent with the verified outputs generated in equilibrium:

$$M_i = \Phi(\, M_i, \{ y_{jt}, v_{jt} \}_{j,t} \,) \quad \text{for all } i$$

where $\{y_{jt}, v_{jt}\}$ denotes the history of outputs and verifications and Φ is the model-update operator. The equilibrium is recursive because Φ feeds back into G_i, which feeds back into a, which feeds back into outputs, which feed back into Φ. The equilibrium is the fixed point of this recursion.

Figure 1. Structure of the Recursive Equilibrium Fixed Point

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        Profile at stage t
     G_t = (G_1, …, G_n)
     M_t = (M_1, …, M_n)
               │
               ▼
   Individual optimization (each agent i)
   a_i ∈ arg max  E[ Q(G_i(·; a_i) | G_{-i}) ]
               │
               ▼
   Model update (each agent i)
   M_i ← Φ(M_i, { y_jt, v_jt }_{j,t})
               │
               ▼
        Profile at stage t+1
     G_{t+1} = (G'_1, …, G'_n)
     M_{t+1} = (M'_1, …, M'_n)

      Ψ : (G_t, M_t) → (G_{t+1}, M_{t+1})

   Fixed-point condition: (G*, M*) = Ψ(G*, M*)

Existence (Prop. 1): Brouwer, under T1–T2
Uniqueness & convergence (Prop. 2): Banach, under T3
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Notes: The composite best-response map Ψ applies individual optimization (Condition 1) and model updating (Condition 2) to a profile of generation functions and domain models at stage t to produce a profile at stage t+1. A recursive equilibrium is a profile (G, M*) satisfying (G*, M*) = Ψ(G*, M*). Propositions 1 and 2 establish conditions under which such a fixed point exists and is unique. [Figure to be redrawn in vector format (PDF, EPS, or AI) prior to submission per Econometrica figure requirements.]*

B. Existence (Brouwer)

The Brouwer fixed-point theorem (Brouwer 1911) asserts that a continuous function from a nonempty compact convex subset of Euclidean space into itself has a fixed point.[5] Define the composite best-response map Ψ: (G, M) → (G', M'), where (G', M') is the profile that results from applying individual optimization and model updating to (G, M). A fixed point of Ψ is a recursive equilibrium.

Proposition 1 (Existence). Let the space of generation functions G_i and domain models M_i admit topologies under which they are nonempty, compact, and convex. Suppose the individual optimization operator and the model-update operator are both continuous. Then a recursive equilibrium exists.

Proof (sketch). The product space of agent characteristics is nonempty, compact, and convex as a finite product of nonempty, compact, convex sets. The composite best-response map Ψ is continuous as the composition of continuous operators. By Brouwer's theorem, Ψ has a fixed point in the product space. The fixed point satisfies Conditions 1 and 2 by construction. ∎

The assumptions warrant interpretation. Compactness of the space of generation functions requires a topology under which generation functions with bounded computational resources form a closed and bounded set. This is satisfied in standard parameterizations of generation functions by bounded-norm weight vectors. Convexity is satisfied for parameter spaces of fixed architecture. Continuity of the optimization and model-update operators is satisfied for smooth objective functions and gradient-based update rules. The existence result operates on a higher-order object than the Arrow-Debreu excess-demand correspondence: Arrow and Debreu (1954) applied fixed-point theory to excess demand over a fixed commodity space, while recursive equilibrium applies it to a best-response map over a space of generation functions.

[5] Kakutani's generalization to upper hemicontinuous correspondences with convex-valued images (Kakutani 1941) is used in the Arrow-Debreu (Arrow and Debreu 1954) and Nash (Nash 1950) existence proofs.

C. Uniqueness and Convergence (Banach)

The Banach fixed-point theorem (Banach 1922) provides a stronger result under stronger conditions: for a contraction mapping on a complete metric space, there is a unique fixed point, and iteration from any starting point converges to it.

Proposition 2 (Uniqueness and Convergence). Suppose the composite best-response map Ψ is a contraction on the product space of generation functions and domain models under an appropriate metric. Then there exists a unique recursive equilibrium, and the sequence (G_t, M_t) generated by repeated application of Ψ from any starting point converges to the equilibrium.

The contraction condition is considerably stronger than the conditions of Proposition 1. It requires that the best-response map reduces the distance between profiles by a factor less than one at each iteration. In economic terms, adjustment of one agent's generation function in response to others' generation functions does not overshoot, and the model-update operator smooths rather than amplifies discrepancies. Whether the condition holds in a given generative network is an empirical question that depends on the specifics of the update rules and the smoothness of the objective functions. Where the condition holds, Computative Economics delivers a stronger equilibrium result than the Arrow-Debreu existence theorem: the latter asserts existence but does not deliver uniqueness without additional monotonicity assumptions and does not deliver a constructive convergent procedure.

D. Comparative Statics and Algorithmic Collusion

Two comparative-statics results follow from Proposition 1. A symmetric increase in computational resources across all agents shifts the equilibrium toward higher possibility-space quality for each agent. An asymmetric increase in computational resources available to a single agent shifts the equilibrium toward higher quality for that agent and either toward or away from higher quality for the others, depending on whether the agents' generation functions are strategic complements or strategic substitutes (Bulow, Geanakoplos, and Klemperer 1985). A related consideration is that Nash equilibrium analysis applies to computative settings with higher empirical fidelity than to human settings because computative agents approximate the rational-actor assumptions more closely than human decision-makers. This has a regulatory implication. Algorithmic collusion, the convergence of independently optimizing agents on jointly welfare-reducing strategies without explicit communication, is a first-order concern in markets populated by computative agents, and its incidence is likely to expand as computative agents penetrate additional market domains.

VII. Four Propositions

The preceding parts yield four propositions. Each stands in contrast to a corresponding feature of scarcity-based theory and generates a distinct research program.

A. Proposition 1: Value from Possibility-Space Quality

Value in computative markets derives from the quality of possibility-space generation rather than from the scarcity of realizations produced. Under the computative primitive, the supply of any specific realization is unbounded because realizations are drawn from a generative distribution that can produce arbitrarily many of them. What is bounded is the quality of the distribution. Value therefore attaches to the distribution rather than to the realization. This implies that markets for computative outputs will organize around access to generative capacity rather than around the exchange of specific outputs, that pricing will be access-based rather than per-unit, and that competition and antitrust analysis should attach to generative capacity rather than to downstream outputs.

B. Proposition 2: Optimization over Generated Alternatives

Computative agents optimize across generated alternatives rather than among a pre-specified fixed set. This distinguishes the framework from both Neoclassical and Behavioral Economics, each of which takes the alternative set as given. Three analytical consequences follow. The scope of economic choice is determined not by the structure of markets but by the structure of generative capacities. The boundary between innovation and ordinary production dissolves: innovation is a continuous feature of the computative agent's activity rather than an exogenous shock. The treatment of innovation as endogenous frontier-shifting originates in Schumpeter (1942, 81-86). The computative framework generalizes the Schumpeterian insight by making endogenous frontier-shifting a constitutive property of the agent. And competition among computative agents is competition over the quality of possibility spaces rather than over a fixed market share.

C. Proposition 3: Distribution Follows Computational Access

Distribution of economic outcomes in a computative economy follows the distribution of access to computational infrastructure rather than the distribution of labor or capital scarcity. This is a positive claim about the primary axis of distributional variation under the computative primitive, not a normative claim about what the distribution ought to be. Under the Neoclassical primitive, factor income distribution reflects marginal productivity and factor supply. Under the computative primitive, cognitive labor scarcity dissolves across the domain where cognitive production is computationally substitutable, and capital scarcity reconstitutes around computational infrastructure. The binding constraint on production is access to computation, and the primary distributional axis therefore aligns with it. The policy consequence is that instruments affecting the distribution of computational access, including competition enforcement over generative infrastructure and governance of decentralized compute markets, are the primary levers of distributional policy in the affected domain.

D. Proposition 4: Policy Targets Computational Access and Objective Function Governance

Policy in computative settings targets computational access and objective function governance rather than price or quantity. Price controls operate on a signal that no longer carries the coordinating information it carries in the Neoclassical economy, Quantity controls operate on outputs whose supply is effectively unbounded at the realization level. Neither is the operative lever. Computational access governance determines which agents can generate at which quality level. Objective function governance determines what agents generate toward. The alignment problem in artificial intelligence (Russell 2019; Kaal 2026c) is, in this framing, a foundational policy problem in Computative Economics rather than an adjacent engineering concern.

VIII. Model Assumptions

The assumptions of the framework specify its domain of applicability. They divide into primitive, technical, and institutional assumptions.

A. Primitive Assumptions

A1 (Computational Primitive). The binding constraint on production is computational. The assumption does not require that physical resources be absent. It requires that the marginal cost of producing an additional realization within an already-generated possibility space approach zero while the binding constraint on the quality of the possibility space itself is computational capacity.

A2 (Generative Agents). Agents are computative in the sense of Part III. Each agent is characterized by a tuple (C, O, M, G, R) and solves the decision problem stated there.

A3 (Endogenous Alternative Sets). The alternative set over which optimization occurs is generated by the agents rather than given exogenously. The generation function G maps (C, O, M) into a distribution over outputs in the possibility space.

A4 (Verifiable Generative Outputs). Outputs generated by agents are verifiable against the objective function O. Verification produces a signal v that updates the domain model M and reputation R. The assumption requires a statistically meaningful fraction of outputs to be verifiable, not verification of every output.

A5 (Non-Transferable Domain-Specific Reputation). Reputation R is non-transferable across agents and domain-specific within an agent.

B. Technical Assumptions

T1 (Topological Structure). The space of generation functions and the space of domain models each admit topologies under which they are nonempty, compact, and convex.

T2 (Continuity of Best Response). The composite best-response operator Ψ is continuous on the product space of generation functions and domain models.

T3 (Contraction for Uniqueness). For uniqueness and convergent iteration (Proposition 2), Ψ is a contraction mapping under an appropriate metric. T3 is sufficient but not necessary for existence (Proposition 1).

T4 (Smooth Objective Functions). The objective function O is continuously differentiable in its arguments.

T5 (Bounded Computational Resources). For each agent, computational resources C are bounded above by a finite quantity. The bound is agent-specific, not common.

C. Institutional Assumptions

I1 (Reputation Infrastructure). A reputation infrastructure exists that records verifiable generative performance of agents and makes the resulting reputation accessible to counterparties. The assumption does not require centralized implementation. Decentralized reputation infrastructures on distributed ledgers satisfy it (Calcaterra, Kaal, and Rao 2018; Calcaterra and Kaal 2021; Kaal 2026b; Kaal 2026d).

I2 (Verification Mechanism). A mechanism exists by which generated outputs can be evaluated against the objective function O. The mechanism may be automatic, social, or hybrid.

I3 (Computational Access Rights). Agents have enforceable rights to the computational resources allocated to them. This is the computative analog of the Neoclassical property-rights assumption.

I4 (Governance of Objective Functions). Mechanisms exist by which agents' objective functions can be verified, contested, and updated through institutional processes.

D. Domain of Applicability

The assumptions specify the domain where the framework applies. That domain is not the whole of economic activity. It is the domain where cognitive and information-intensive production is the dominant mode and where computative agents are the dominant producers. Where these conditions do not hold, Neoclassical Economics remains the appropriate framework. The two paradigms coexist, each with its own domain of application, and the boundary between them shifts as computational abundance extends to new categories of production. The coexistence is not a methodological compromise but a feature of economic theorizing under technological transition, analogous to the coexistence of classical and neoclassical frameworks in the decades following the marginalist formulation.

IX. Governance Infrastructure

Every economic framework implies a governance infrastructure. Neoclassical Economics implies property rights, contract enforcement, monetary policy, and antitrust. The New Institutional Economics extends this to firms, hierarchies, and the rules of the game more broadly. Computative Economics implies a governance infrastructure organized around the primitives developed in Parts III through VIII. Four elements are foundational: dynamic regulation adequate to the pacing of computative change; reputation-based verification infrastructure; decentralized coordination architecture; and commons governance translated from the Ostrom tradition to the computational domain.

A. Dynamic Regulation

Static regulatory frameworks calibrated to legislative timescales cannot govern technologies that evolve on exponential timescales. The pacing problem, the systematic lag between technological change and regulatory response, is structural rather than contingent on institutional speed (Kaal 2016). Dynamic regulation, institutional architecture that self-adjusts in response to technological change through built-in feedback mechanisms, is a precondition for effective governance of the computative domain. The delegated-acts and code-of-practice mechanisms adopted under recent artificial-intelligence statutes represent partial steps in this direction but remain tethered to legislative revision cycles that operate at substantially lower frequency than the technology they govern.

B. Reputation-Based Verification

Reputation infrastructure is the institutional complement to the computative agent. Without a verification record that makes generative performance accessible to counterparties, the market for generative outputs is subject to the lemons failure characterized by Akerlof (1970) for asymmetric-information goods markets. The computative analog is a generative-quality failure: when the quality of a generative distribution is unobservable, counterparties price on the distribution of observed qualities, which systematically underprices high-quality generators. The infrastructure requirements are four: a verification mechanism against stated objectives; a tamper-resistant accessible record of verifications; a mapping from verifications to a reputation score predictive of future performance; and a non-transferability constraint. Distributed-ledger reputation systems satisfy these requirements by construction.

C. Decentralized Coordination

Coordination in computative settings occurs through generative networks rather than through traditional hierarchies or Neoclassical markets. The generative network is decentralized in the sense that coordination occurs through the interaction of generation functions rather than through a central coordinator. This property is structural rather than optional. A central coordinator would itself be a computative agent whose generation function would be subject to the equilibrium conditions of Part VI, producing an infinite regress that is resolved by abandoning the coordinator.

D. Commons Governance under Generated Outputs

Generated outputs in computative settings are non-rival: a single realization can be consumed by an unbounded number of agents without diminishing its availability to others. The underlying generative capacity, however, is rival: the computational resources required to produce generative outputs remain finite and allocated. This combination, non-rival outputs drawn from rival generative capacity, is a generalized commons problem. It is neither the classical private-good problem to which Neoclassical Economics is calibrated nor the public-good problem for which the Samuelson welfare apparatus was developed. It is a commons problem in the sense of Ostrom (1990), and it requires Ostrom's analytical apparatus.

Ostrom (1990) identified eight design principles characteristic of commons governance regimes that sustain common-pool resources over time: clearly defined boundaries; proportionality between benefits and costs; collective-choice arrangements; effective monitoring; graduated sanctions; conflict-resolution mechanisms; recognition of self-governance rights; and, for larger systems, nested enterprises. The principles were derived from studies of physical commons. Their application to the computative commons requires translation and produces an inversion of the governance object.

Ostrom's principles were developed for scarce common-pool resources where the governance task is preventing overuse that would exhaust the pool. The computative setting differs: the realization-level pool is non-rival, so overuse does not diminish availability, but the generative-capacity pool is rival, and overuse of computational resources, degradation of training data through adversarial manipulation, or capture of model architectures by concentrated interests can exhaust the generative substrate on which the commons depends. The governance task therefore shifts from preventing consumption-level exhaustion to preventing generation-level degradation. Ostrom's principles do not lapse under this shift; they become the primary rather than secondary institutional layer of the framework.

The translation is specific. Clearly defined boundaries correspond to specification of which agents count as participants in a generative network, typically through non-transferable domain-specific reputation. Proportionality corresponds to reputation-weighted allocation of both generative opportunity and governance voice. Collective-choice arrangements correspond to on-chain governance protocols that permit participants to modify the rules of the network. Effective monitoring corresponds to cryptographic verification of outputs against stated objective functions. Graduated sanctions correspond to reputation-based consequences that scale with the severity of violations. Conflict-resolution mechanisms correspond to on-chain dispute-resolution protocols with appeal pathways. Recognition of self-governance rights corresponds to the principle that generative networks are governed by their participants rather than by external authorities. Nested enterprises correspond to the layered architecture by which local generative networks compose into federated networks through verified cross-network reputation.

The Ostrom-based governance architecture is consistent with the institutional requirements of Computative Economics and is partially implemented across decentralized autonomous organization designs. The framework developed here identifies the generative commons as the institutional object of the framework and states Ostrom's principles, translated to the computational domain, as the design principles that govern it.

X. Distinction from Adjacent Frameworks

Computative Economics is a standalone framework. It is not a variation on, correction of, or specialization within any of several adjacent frameworks with which it might be confused. This part distinguishes the framework from four such frameworks: post-scarcity theory, the zero marginal cost society, digital platform economics, and the knowledge economy literature. It also positions the framework in relation to the abundance-society argument of Desai and Lemley (2022).

Post-scarcity theory in its various formulations asserts that technology can deliver material abundance sufficient to eliminate the scarcity problem. Computative Economics differs in four respects. It is analytical rather than normative or prophetic. It specifies the successor framework that post-scarcity theory typically leaves blank. It does not assert abundance simpliciter. It asserts abundance in the realization-level supply of generative outputs while retaining scarcity in computational capacity, domain expertise, and governance capacity. And it applies to specific domains rather than to the whole of economic activity, preserving Neoclassical Economics as the framework for the remaining domains.

Rifkin (2014) describes a trajectory in which information technology drives the marginal cost of producing information-intensive goods toward zero. Rifkin's framework is descriptive and predictive rather than theoretical in the present sense; it identifies an empirical trajectory without constructing the analytical apparatus that would govern the post-trajectory economy. Computative Economics is the analytical apparatus Rifkin's trajectory lacks.

Digital platform economics, developed in Rochet and Tirole (2003) and successors, analyzes two-sided and multi-sided markets in which a platform intermediates between distinct user groups. The framework extends Neoclassical Economics to handle network externalities, cross-subsidization, and distinctive pricing structures but remains within the Neoclassical primitives. Computative Economics is not a generalization of platform economics. Its primitives differ. A computative agent is not a platform user in the platform-economic sense, and the equilibrium concept is recursive rather than competitive.

The knowledge economy literature, associated with endogenous growth theory (Romer 1990), treats knowledge as a factor of production with distinctive properties. The framework retains the Neoclassical primitives and introduces knowledge as a specific kind of good with non-standard properties. Computative Economics takes a different step: where the knowledge economy treats knowledge as a good with distinctive properties, Computative Economics treats the generative distribution as the object of analysis, with individual realizations as draws from it. The shift is in primitives rather than in properties of an existing primitive.

The abundance-society argument of Desai and Lemley (2022, 2023) shares the diagnostic premise of the present paper: technologies of abundance democratize and decentralize production across expanding categories of goods, and legal institutions built on scarcity must respond. Desai and Lemley survey the legal and institutional responses from an intellectual-property and information-law perspective. Computative Economics operates at a different level: it constructs the analytical apparatus the post-abundance economy requires rather than surveying the legal responses. The two frameworks are complementary. Desai and Lemley identify the governance question the abundance transition raises. Computative Economics provides the analytical primitives required to answer it.

XI. Open Problems

The framework as developed defines a set of open problems that structure the research program. Five are foundational.

First, further development of the recursive equilibrium theory. Propositions 1 and 2 establish existence and, under contraction, uniqueness and convergent iteration, but the comparative-statics properties, the conditions under which convergence is local versus global, the behavior of equilibria under perturbation of the agent population, and the conditions under which multiple equilibria persist remain open.

Second, operationalization of possibility-space quality. The four quality functionals of Part IV.B, coverage, precision, robustness, calibration, provide a conceptual framework, but their operationalization into measurable quantities and the empirical methods for comparing quality across generation functions remain to be developed.

Third, national accounts for computative production. Existing national accounts are designed to measure terminal human consumption and do not capture intermediate value created in agent-to-agent transaction chains where no human consumption event occurs at any step prior to the terminal output. The measurement apparatus requires reconstruction.

Fourth, institutional design for computational access governance. Proposition 3 identifies access to computational infrastructure as the primary distributional axis under the computative primitive, and Proposition 4 identifies computational access and objective function governance as the primary policy targets. The specific institutional mechanisms required to implement these policy targets, their legal form, their enforcement structure, and their interaction with existing competition and administrative law, remain to be specified.

Fifth, the normative foundations of evaluation under the computative primitive. The standard welfare theorems lose their foundation in the computative domain, as shown in Part IV.C. The distinction between terminal and proximate consumption (Part II.D) suggests that human welfare remains the evaluative criterion at the terminal level, but the analytical apparatus for connecting intermediate agent-to-agent activity to terminal human welfare assessment remains to be developed.

XII. Conclusion

Paradigm shifts in economic thought have involved changes in the foundational primitive of the discipline rather than refinements of existing machinery applied to new phenomena. The classical framework took the distribution of social product among land, labor, and capital as its primitive. Neoclassical Economics took the choice of a rational agent under scarcity as its primitive. Each successor framework did not refute its predecessor within the predecessor's proper domain; it constituted a new analytical apparatus applicable where the predecessor's primitives did not hold.

The present paper proposes such an apparatus for the domain in which the computational primitive holds. The computative agent, characterized by the tuple (C, O, M, G, R), replaces homo economicus as the analytical primitive. The generated possibility space replaces the scarce good as the object of analysis. Recursive equilibrium replaces competitive equilibrium as the coordinating concept, generalizing the existence argument of Arrow and Debreu (1954) to the case of endogenous generation functions. Existence is established via Brouwer (1911) under continuity and convexity. Uniqueness and convergent iteration are established via Banach (1922) under an additional contraction condition. Four propositions follow from the framework, and fourteen model assumptions specify the domain where it applies. A governance infrastructure is developed that includes a translation of Ostrom (1990) to the computational domain, where the relevant commons is the generative substrate rather than the realization-level pool. The framework does not displace Neoclassical Economics within the domain where the scarcity primitive holds. It constitutes a companion paradigm applicable where the computational primitive holds, with the boundary between the two domains an object of empirical investigation and the subject of the open problems stated in Part XI.

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