Observer-Centric: The Lazy Update World Model

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Abstract

This model addresses the long-standing **"impossible triangle"** in **game development**—the inherent trade-off among world scale, content fidelity, and production cost. Traditional, **object-centric architectures** rely on per-frame updates with **O(N)** computational complexity, causing performance to degrade linearly as the world grows.

Guided by a **principle of minimal computation**, the model computes only those objects perceived by internal observers, avoiding wasted work. It introduces a **potential state** in which the vast majority of unobserved objects continue to exist with logically defined evolution, while their computation is deferred and performed only upon subsequent **observation (lazy update)**. Building on this foundation, two complementary laws define a unified temporal system that is both logically self-consistent and causally complete: **Law I (Observer Effect & Lazy Update)** governs retrospective reconstruction when observation occurs, and **Law II (Observer Intervention & Causal Chain Settlement)** governs prospective outcomes when interventions generate future causal chains to be settled by a central scheduler.

The core contribution is to shift computational complexity from **O(N)**, tied to the total number of objects, to **O(K)**, tied only to the number of observed objects. The clock experiment in the "Strangest Experiment" validates this scale invariance, indicating a viable path toward virtual worlds of unprecedented scope.

This theoretical advantage comes with substantial practical challenges in three areas: (1) strong mathematical-modeling requirements for development teams; (2) fundamental conflicts with existing engine architectures that imply significant refactoring costs; and (3) a new debugging paradigm. Overall, the model constitutes a **high-risk, high-reward** framework that offers deep philosophical and engineering insights for constructing future virtual worlds.

Introduction: Bottlenecks in Virtual World Development and a Path Forward

Conventional game development faces a fundamental dilemma: how can larger worlds be created under fixed computational budgets? As world scale grows, computational cost rises linearly or even exponentially, becoming the bottleneck that constrains virtual-world progress. In open-world games, for example, simulating tens of thousands of square kilometers, millions of objects, and complex ecosystems often leads to falling frame rates, soaring hardware demands, and even endlessly prolonged production cycles. This tension not only limits immersion but also hampers authentic interactions among AI agents.

The solution proposed here arises from a practical need: while designing a game-AI system built on a **hybrid cognitive–affective–social architecture**, the internal logic became extremely complex, demanding substantial compute to operate and to validate underlying theories. The AI system adopts a **Multi-System Synergistic Cognitive Architecture (MSSCA)**—an **eight-layer**, modular design in which each layer has a clear role, and information flow with feedback forms a complete **perception–cognition–action loop** for agents. Within this stack, the perception layer serves as the entry point, receiving external inputs and converting them into internal representations. This inspired a shift in the world model from an **object-centric** to an **observer-centric** paradigm, aligning more naturally with the AI's perceptual prediction mechanisms and markedly reducing overall computational load.

On this basis, a **Principle of Minimal Computation** is introduced: if frame-by-frame integration and one-shot computation are equivalent in outcome, why compute unobserved objects every frame? Compute is always limited, which forces choices. The core design binds object state updates to the perceptions of internal observers. Unobserved objects remain in a **potential state**—not nonexistent, but deferred in computation. This is a pragmatic choice under resource constraints and an embodiment of minimal computation for efficiency. With this shift, complexity moves from **O(N)** to **O(K)**—where **N** is the total number of objects and **K** is the small subset within the observer's range—enabling large-scale worlds.

Two complementary laws complete a closed temporal system: **Observer Effect & Lazy Update (Law I)** and **Observer Intervention & Causal Chain Settlement (Law II)**. Law I looks to the past, back-computing the states that should have been, ensuring logical self-consistency. Law II looks to the future, predicting necessary outcomes and preserving the integrity of the causal chain. The two operate in tandem so that, even under extensive lazy computation, causality remains intact. At the same time, the model indirectly respects physical conservation principles (e.g., conservation of energy and the increase of entropy), albeit realized through an abstract, deferred-computation form.

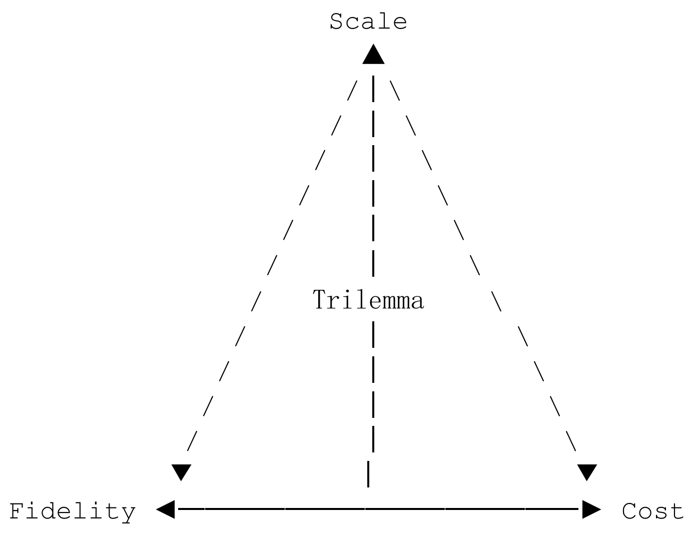
External observers and the virtual world inherently occupy different layers of description, creating an objective asymmetry. Directly transplanting real-world continuous physics into a virtual world is impractical, because digital computation admits superior algorithmic strategies. Leveraging this asymmetry makes it possible to achieve efficient, high-fidelity simulated worlds within limited compute budgets. This approach not only breaks the "impossible triangle" bottleneck of traditional architectures but also delivers an internally consistent experience for in-world AI agents and players.

Structure of this paper: the discussion begins with problem analysis, then unfolds the core concepts, the proposed solution, practical validation, and future outlook. Readers will see how to achieve the same experiential outcomes with far less computation and explore the model's practical potential in real-world game development.

Chapter 1: Problem Analysis — Why a New Model Is Needed

1.1 The Open-World Trilemma

1.1.1. Modern game development faces a fundamental trilemma:



Meaning of the triangle:

1. **World Scale (Scale)**

- **Map size:** expanding from a few square kilometers to thousands, or even simulating an entire planet (e.g., *Microsoft Flight Simulator* employs satellite data to generate a global map [1]). However, larger scale means more regions must be loaded in real time, driving computational costs up—often exponentially [2].
- **Object count:** from thousands to millions of interactive entities, including trees, buildings, and dynamic objects. Tracking positions and states for these entities continuously leads to surging memory usage [3].
- **NPC count:** from dozens to tens of thousands of agents, each requiring independent decision-making and interaction. As AI grows in complexity, simulating large numbers of NPCs becomes a performance bottleneck and can cause frame-rate drops under traditional methods [4].
- **System complexity:** the scale of ecological, economic, and social systems—for example, simulating weather changes, market fluctuations, or NPC social relationships. These systems must interact in real time, further amplifying computational demand [5].

2. **Content Fidelity (Fidelity)**

- **Physics simulation:** precise collision, destruction, and fluid dynamics (e.g., *The Legend of Zelda: Breath of the Wild* features a physics engine that enables object interactions [6]). High fidelity requires complex formulas every frame, consuming GPU resources and making it difficult on lower-end hardware to sustain high frame rates [7].
- **AI complexity:** independent decision-making, memory, and emotion modeling for each NPC. Sophisticated AI—such as enemy behaviors in *The Last of Us Part II* leveraging advanced AI techniques—becomes extremely costly to scale [8].
- **Depth of interaction:** the ability to interact with and alter virtually every object—for instance, environmental destruction or player-driven construction. High interactivity boosts immersion but demands storage for vast numbers of state changes [9].
- **Visual quality:** high-precision models and real-time ray tracing (e.g., Nanite in Unreal Engine 5 [10]). By 2025, real-time rendering advances allow greater fidelity, but trade-offs often sacrifice

scale [11]. Dynamic resolution scaling has become a common optimization to balance fidelity and performance [12].

3. **Cost**

- **Computational resources:** CPU, GPU, and memory consumption. Open-world titles must process massive datasets, and traditional per-frame updates lead to high power usage and heat generation [13].
- **Development cost:** content production, testing, and optimization. Team sizes range from dozens to over a thousand, with schedules stretching from two years to five or more. Reports indicate that by 2025, rising competition and expectations have increased development costs and the share of developers working more than 40 hours per week [14].
- **Operational cost:** servers, bandwidth, and electricity. Multi-platform support (e.g., PC, console, mobile) pushes costs even higher [15].
- **Hardware requirements:** minimum-spec thresholds. High-fidelity games often require top-tier hardware, constraining the potential player base [16].

1.1.2.Compromises Under Traditional Architectures

Choice	**Sacrifice**	**Typical Example**	**Outcome**
Large Scale + High Fidelity	Extremely high cost	*Microsoft Flight Simulator*	Requires top-tier hardware and cloud support; development costs in the hundreds of millions.
Large Scale + Low Cost	Low fidelity	*Minecraft*	Simplified block-based world, sacrificing visual and physical realism.
High Fidelity + Low Cost	Small scale	*The Last of Us*	Linear levels and constrained spaces; free exploration not possible.
Large Scale + High Fidelity + Aggressive Optimization	Schedule slippage	*Cyberpunk 2077* (launch version)	Frequent bugs in the initial release; stability sacrificed in pursuit of scale and fidelity.

1.1.3.Why it is a "trilemma"

- **Traditional architectures continuously compute per-object state:** even when players do not observe certain entities, the system may still update them, wasting resources [17]. When world size doubles, total computation typically grows linearly [17], while fidelity (e.g., physics simulation complexity) often scales exponentially [20].
- **Doubling scale ≈ doubling cost (near-linear):** tens of thousands of NPCs must be processed in parallel; under conventional methods this imposes high CPU load [19][25]. Reports indicate that higher entity density constrains graphical fidelity [18][19].
- **Increasing fidelity ⇒ exponential compute growth:** real-time ray tracing or complex AI demands more GPU cycles [20][22]. In high-fidelity open worlds, interaction depth is often curtailed to keep costs manageable.
- **All three dimensions cannot be maximized simultaneously:** techniques like LOD (level of detail) and dynamic scaling are trade-offs rather than fundamental fixes [21][22]. Trends in 2025 show AI and XR integration amplifying these pressures, calling for a new paradigm to break the triangle [23][24].

1.2 Fundamental Defects of Traditional Game Architectures

Traditional game architectures are **object-centric**. In mainstream engines, this typically means executing `Update/Tick` on enabled objects/Actors every frame. As object counts grow, this default per-frame polling accumulates into a significant CPU burden. Official documentation and performance guides therefore recommend disabling unnecessary **`Update/Tick`**, reducing tick frequency, or switching to event-driven patterns [26][27][33]. However, if causal continuity is to be preserved, relying on **`Update/Tick`** is, in practice, unavoidable.

In open worlds, without effective interest management/visibility filtering and partitioned streaming, the system must still periodically process large numbers of entities outside the camera frustum and interaction radius. Research and engines thus provide interest management and World Partition–style on-demand loading, but these mechanisms alleviate rather than cure the issue at its root [17][28].

Moreover, increasing object counts raises render-side draw-call and state-change overhead, creating main-thread bottlenecks. Recent techniques such as Work Graphs/Mesh Nodes and batching specifically target this problem [18][32]. On the player side, recent GDC sessions and media coverage highlight **"open-world fatigue"**: engagement with world activities is often low, requiring stronger guidance and structure to raise participation (e.g., from **roughly 15%** toward a **50% target**) [30][31].

Core Defects：

1. Global, Continuous Logic Computation

- **Explanation:** In mainstream architectures (e.g., Unity's **`Update()`** / Unreal's **`Tick`**), enabled objects run logic every frame by default. Unless explicitly disabled—or unless interest management/partitioned streaming and visibility culling are employed—distant trees, NPCs, and environment objects are still polled or prepared for the rendering pipeline, incurring unnecessary CPU/GPU overhead [26][27][28][33]. (Background: interest management filters updates and distribution by relevance [17].)
- **Impact:** As object/instance counts rise, draw calls and render state changes push the main thread toward bottlenecks; optimization then depends on reducing batch counts/merging, etc. Official manuals and technical papers note that preparing draw calls and switching states often costs more CPU time than the draw itself, and multithreaded rendering is constrained by state changes and driver overhead [29][30] (also see pipeline/batching guidance in [18][19]). To sustain frame rate, projects frequently introduce LOD/HLOD and dynamic resolution scaling—trade-offs that do not fundamentally eliminate computation.
- **Example:** At launch on PS4/Xbox One, *Cyberpunk 2077* exhibited notable stability and frame-rate issues. On 2020-12-17, Sony delisted the title from PS Store and offered full refunds; on 2022-02-15, Patch 1.5 explicitly addressed crowd behavior/reactions, pathfinding, and culling (some changes not applicable to last-gen consoles), exemplifying the trade-off between system complexity and performance in dense open worlds [35][34][36].

2. Linear Complexity and Scaling Bottlenecks

- **Explanation:** The typical real-time architecture follows a per-frame "object update" paradigm: each game loop iteration traverses the object set and calls each object's `Update/Tick`. Time complexity thus grows linearly with the number of objects—**O(N)**. When **N** doubles, CPU-side scheduling/scripting roughly doubles as well [26][27][37]. To mitigate this inherent linear cost, industry practice uses data-oriented approaches (ECS/DOTS), interest management, and on-demand loading to shrink the set of objects that actively participate in updates (making "N" smaller), rather than changing the complexity class of the paradigm itself [17][29]. (For the semantics and origins of the **O(N)** pattern, see [37].)
- **Impact:**

  1. **Scale and fidelity constraints.** In large worlds, pathfinding and navigation data amplify problems in both space and time. GDC AI tracks explicitly note that pathfinding in massive scenes can cause stutters or blow memory budgets, slowing content iteration [38]. Large crowds often adopt a layered strategy—"a small number of real AI + many low-cost proxies." For example, *Assassin's Creed Unity* demonstrations reportedly used ~40 fully simulated AIs to support the presence of tens of thousands of NPCs, an engineering trade-off addressing **O(N)** decision and memory costs [39].
  2. **Tighter budgets for XR/high refresh rates.** In VR/AR (XR), common 72/80/90 Hz targets restrict the per-frame time budget to ~13.9/12.5/11.1 ms. The more linear updates there are, the harder it is to meet these targets, hence reliance on foveated/peripheral trade-offs (e.g., eye-tracked rendering) to free budget [40][41][42]. (This is not exponential complexity, but linear work accumulating under stricter frame times, making scaling "harder.")
  3. **Player-side feedback.** When compute/production budgets are constrained, open worlds are more prone to "filler content/low engagement." Recent GDC talks and media use "open-world fatigue" to describe this and advocate structured guidance to lift participation [30][31] (continuing the evidentiary chain from §1.2).

- **Example:** *Microsoft Flight Simulator* (2020) offloads petabytes of geospatial data and parts of the computation to Azure for preprocessing/streaming. Official technical articles and media repeatedly note reliance on Bing Maps/Blackshark.ai and cloud-side AI to generate and stream world data on demand; when offline or bandwidth-limited, the experience falls back to local/cache and simplified scenes, not equivalent to cloud quality [1][43][44]. (Community/support documents likewise explain that disabling online features or lacking bandwidth triggers offline/cache modes with a degraded experience.)

3. Uneven Resource Allocation and Development Trade-offs

- **Explanation:** At any moment, players attend to only a small view and interaction radius, yet traditional per-frame updating still routes large numbers of irrelevant objects through "update/visibility/render-prep" paths, wasting global computation [26][17]. As a result, engines and research emphasize visibility/occlusion culling and partitioned streaming to shrink the "truly necessary set" of objects: Unity's occlusion culling allows only camera-visible objects into rendering at runtime; Unreal's World Partition + HLOD dynamically loads/unloads grid cells and low-detail stand-ins for distant content, keeping far, non-interactive objects out of the pipeline [45][46]. (This fundamentally reduces **N**, rather than changing the **O(N)** paradigm.)
- **Impact:**

  1. **Design:** navigational confusion, repetitive content, and "open-world fatigue." GDC 2025 sessions and media report low participation in abundant activities, advocating stronger guidance to raise participation from ~15% toward 50%; "exploration anxiety/choice overload" can suppress self-directed exploration [30][31].
  2. **Production and quality:** manpower and schedules are diluted, increasing pre-release compromises/delays. The GDC 2025 *State of the Industry* report indicates roughly 1 in 10 workers experienced layoffs within a year; the industry is broadly under pressure, squeezing QA and polish. Consequently, more projects publicly adopt "delay for more optimization/certification" as a tactic (numerous recent flagship titles have been postponed with "additional polish/certification" cited) [47][48]. (This point is a reasonable inference drawn from layoff and delay reports, not a quantitative claim such as "bug rate +20%.")

- **Examples:**

  1. **CPU/system load and compromises:** *Dragon's Dogma 2***.** At release, CPU-side load from numerous NPCs in dense city scenes led to significant frame-rate drops; technical media benchmarks corroborated the pattern "approach NPCs → more pronounced CPU bottlenecks," with subsequent official optimizations rolling out over time [49][50]. Such cases show that when the density of visible/relevant activity is high, even a small area can overwhelm the frame budget.
  2. **Cost and long-cycle optimization: the** ***GTA*** **series.** Historically, *GTA V*'s development + marketing budget has been widely reported at roughly $265 million (a record at the time). Figures of $1–2 billion for *GTA VI* are analyses/rumors and not confirmed by Rockstar/Take-Two: mainstream business media and analyst reports commonly contend it may be among the most expensive/profitable games ever, while other outlets publish rebuttals of exaggerated "$2 billion" claims. Regardless of the final number, the consistent signal is that the series' enormous scale and expectations entail multi-year optimization and massive resource commitments [51][52][53][54].
  3. **Engineering counter-moves toward "more controllable maps."** Confronted with big-map costs and pacing issues, some 2024–2025 releases and commentary trends favor smaller but more structured spaces/gradual, gated partitions to gain tighter pacing control and more concentrated resource use [55].

1.3 The Fourfold Pressure of Real-World Constraints

The open-world "trilemma" (world scale × content fidelity × cost) is not an abstract paradox; it is reinforced by four concrete pressures: limited computational resources, hardware diversity, rising development costs, and escalating player expectations. Evidence for rapidly rising budgets and increasingly common delays is well documented—for example, historical GDC surveys reported that "44% of developers said their projects were delayed due to the pandemic" [47][59].

Core Pressures

1. Limited Compute (Frame Budget and Simulation Load)

- Open worlds are prone to frame-budget pressure on CPU/GPU under high-density scenes because per-frame updates/simulation accumulate. The semantics of traditional `Update/Tick` mean that enabled objects are invoked every frame, requiring visibility/occlusion culling, partitioned streaming, and tick-rate reduction to minimize the "set of objects being processed" [26][27][28][45].
- Pursuit of higher visual quality/realism (e.g., global illumination/path tracing, complex physics/particles) significantly increases GPU cycles; public benchmarks and vendor technical documentation confirm the heavy frame-rate impact of these features [7][18][19][20][25][33]. For instance, *Cyberpunk 2077*'s RT Overdrive and related reviews demonstrate very high performance costs; NVIDIA/AMD developer articles also analyze how physics and draw-call/pipeline behavior affect throughput [7][18][20][25].

2. Hardware Diversity (Cross-Platform and Tiered Performance)

- On PC, CPU/GPU generations span a wide range, while consoles/handhelds/VR target distinct refresh rates and resolutions (e.g., ~72/80/90 Hz in VR impose strict frame budgets). Teams are therefore pushed into more aggressive trade-offs between performance and quality (DLSS/FSR, dynamic resolution scaling, variable-resolution shadows/reflections, etc.) [16][40][42][12]. Steam hardware surveys and VR platform documents reflect this "wide-spectrum configuration" reality.

3. Rising Development Costs (Structural Increases in Budget and Schedule)

- Regulatory disclosures: the UK Competition and Markets Authority (CMA), in its Microsoft–Activision report, recorded feedback from multiple major publishers indicating that recent AAA development budgets have generally risen from $50–150M years ago to $200M+ (development), with some single-title series exceeding $250M for development alone; marketing commonly falls in the $50–150M range. In certain phases, combined development + marketing for large franchises can reach several hundred million dollars [56].
- Media and commentary continue to discuss budget inflation and risk aversion trends; additionally, per Ampere analysis, the delay of *GTA VI* was projected to create an approximately $2.7B shortfall in the 2025 market, indirectly evidencing the coupling between mega-project timelines and industry volatility [52][58].

4. Escalating Player Expectations ("Size/Look/Stability" as a Triple Mandate)

- Players simultaneously expect larger worlds, higher precision, and stable frame rates, thereby raising targets on all fronts. On one hand, planet-scale, cloud-assisted AI/data-streamed works such as *Microsoft Flight Simulator* have elevated the baseline for "scale"; on the other, market data show player hours concentrating in flagship and live-service titles, pushing new releases to differentiate with higher production values [1][43][44][57]. This "arms race" in size and quality further intensifies both budget pressure and frame-budget pressure [20][22].

1.3.2 Summary

These four pressures amplify one another, forcing architectural and production-pipeline innovations (ECS/DOTS, Work Graphs, World Partition/HLOD, occlusion/visibility systems, scalable rendering, and content-LOD pipelines, etc.). The shared objective is to minimize the *deliverable N* within limited frame budgets and finite funding, while maintaining the most workable balance of the trilemma [28][29][18][45][21][12].

1.4 Why Change Is Necessary Now

The defects of traditional game architectures and real-world constraints have compounded to a critical point. In 2025 the industry stands at a "crossroads," visible in three developments:

- **(A) Rising costs and risk (layoffs/self-funding/delay risk co-existing)** — The GDC 2025 report notes that 11% of developers were laid off in the past year, 41% were affected by layoffs, and half are self-funding; PC remains the primary platform for 80% of teams [60][61][62].
- **(B) Player attention captured by flagships and long-running titles** — According to Newzoo, in 2024 only 12% of total player time came from new releases; to break through, new projects must raise production values or differentiate more clearly [57][65].
- **(C) Growth slowing to low single digits** — 2025 global games-market forecasts have been revised down by multiple firms: Newzoo at +3.4%, MIDiA at +4.6%, roughly in line with inflation [66][67].

⇒ **Conclusion:** No change = greater exposure to uncertainty (a harder-to-absorb chain reaction across budget, schedule, quality, and reputation).

Core Reasons

1) Technology boom amplifies compute and production pressure

- **Explanation:** By 2025, generative AI has penetrated workflows, but sentiment is split—52% report company-level GenAI use, about one-third of individual developers use it, and perceptions of "negative impact" are rising; GDC 2025 also shows only 4% are required to use AI in their roles [60][61][62]. These technologies (AI-driven NPCs/production, cloud-side pipelines, XR real-time reconstruction, etc.) raise the bar for real-time simulation and toolchain parallelism (see NVIDIA ACE, radiance-field/XR surveys). Traditional per-frame/object-oriented architectures are inherently constrained at large-scale parallelism and scalability, requiring data-oriented and pipelined upgrades—ECS/DOTS, Work Graphs, scalable rendering/LOD—to offset the pressure [23][24][18][29].
- **Impact:** Without architectural upgrades, the combination of rising complexity × tight frame budgets × growing asset scale will more frequently push projects toward delay or feature cuts.
- **Example (evidenced):** Unity's *2025 Gaming Report* shows median build size rising ~67% from 2022→2024 (100 MB → 167 MB), while 88% of teams perceive player session length increasing—together directly amplifying performance and content-delivery pressure [63][64].

2) Slower market growth alongside cost pressure

- **Explanation:** Multiple trackers place 2025 industry growth in low single digits (+3.4% Newzoo; +4.6% MIDiA), insufficient to cover endogenous cost inflation [66][67]. Meanwhile, regulation and tighter capital push more teams toward self-funding [62]. Delays of flagship projects materially drag annual totals—for instance, the official shift of *GTA VI* to May 2026 led several firms to cut 2025 forecasts (Ampere estimates a ~$2.7B shortfall for 2025) [73][58].
- **Impact:** Sustainability pressures are rising—studios are focusing more on energy/cost efficiency (e.g., Xbox developer energy tools and power-saving practices); architectural "efficiency dividends" become a necessity [76].
- **Example (evidenced):** CMA merger-review disclosures indicate AAA development budgets have generally risen to $200M+ for development alone, with marketing commonly $50–150M; rigidity in costs plus longer cycles leaves minimal margin for error [56].

3) Higher player expectations and fiercer competition; distribution rules are changing

- **Explanation:** Players are simultaneously raising the baseline for world size, visual fidelity, and stability (cf. planet-scale baseline and cloud technologies showcased by *Microsoft Flight Simulator*) [1][43][44]. At the same time, EU DMA-driven distribution changes (iOS opening to alternative stores and web installation in the EU), along with Epic Games Store on mobile and the Xbox mobile store (starting on the web), are reshaping cross-device and cross-ecosystem targets [67][69][70][71].
- **Impact:** Products must iterate faster and ship with stronger portability/scalability, or they will lose ground in multi-endpoint environments.
- **Example (evidenced):** Apple announcements and European Commission communications confirm DMA requirements and compliance changes [67][69]; Epic announced EGS Mobile on

EU iOS and global Android [70]; Xbox announced a web-first mobile store to bypass closed-ecosystem constraints [71].

4) Industry instability and the “innovate-or-die” dynamic

- **Explanation:** GDC 2025 shows layoffs affecting 41%, with 11% personally laid off—pressure on both morale and cash flow. Divergent attitudes toward GenAI reflect a tug-of-war between efficiency demands and concerns over quality/ethics/compliance [60][61][62].
- **Impact:** Independent and mid-small teams are more vulnerable in funding and distribution, yet more motivated to adopt higher-efficiency, parallelizable, and reusable stacks (ECS/job graphs/automated production & QA/cloud-native backends) to reduce unit content cost, shorten loops, and control energy use [18][29][76].
- **Example (evidenced):** The spillover effects of *GTA VI*'s postponement to 2026-05 (e.g., rescheduled release windows, trimmed 2025 market size) have been tracked by Reuters and analyst firms [73][18][58].

1.4.2 Summary

- **Data indicate:** low growth × high costs × high expectations × shifting distribution have combined into a chokepoint-like systemic pressure.
- **Path forward:** adopt architectures/production paradigms centered on ECS/DOTS, Work Graphs, World Partition/HLOD, DRS/LOD, automated content & QA, observability and energy-use tooling. The shared objective is to minimize “objects/pixels that must be processed per frame” and the “content-per-dollar delivery risk” within limited frame budgets and finite funding, while adapting to cross-device/cross-ecosystem distribution changes [18][28][29][45][46][76].

1.5 The Shackles: The Essence of the Problem

The shackle of conventional thinking: “The world must run realistically, and all objects should be continuously updated, so that logical continuity and correctness are guaranteed.”

Three key questions:

1. **Why compute what cannot be seen?**
   If a tree falls in a forest and no one sees it, does it really need to be computed every frame?
2. **Why simulate the process frame by frame?**
   If mathematics can directly compute the result, why simulate it step by step?
3. **Why can’t computation be deferred?**
   If 99.9% of the computation has no effect on the current player experience, why shouldn’t it be postponed?

1.6 The Key to Breaking the Trilemma

1.6.1 Core Insight: An Observer-Centric World Model

Traditional (object-centric) model:

- Each object exists and updates autonomously.
- Updates occur regardless of whether it is observed.
- The world “runs objectively.”

New (observer-centric) model:

- Only what is observed needs to be computed.
- Unobserved entities remain in a **potential state**.
- The world is presented with **on-demand, deferred** realization.

1.6.2 Not Corner-Cutting, but Intelligent Resource Allocation

Traditional model: even (flat) allocation of compute

- Important objects: **1%** of resources
- Secondary objects: **1%** of resources
- Irrelevant objects: **98%** of resources (**waste**)

Observer-centric model: on-demand allocation of compute

- Observed objects: **90%** of resources (**fully computed**)
- Potentially observable: **9%** of resources (**pre-compute/readiness**)
- Never observed: **1%** of resources (**maintenance …**)

1.6.3 A Practical Route to Break the Trilemma

Using **lazy updates** and **compressed evolution**:

World scale: supports **millions of objects** ✓

Content fidelity: each object can remain **highly complex** ✓

Cost: compute **only what is necessary** ✓

Trade-off: requires architectural redesign
Benefit: 10–100× performance improvement

A common belief in traditional game development is that the world must "run realistically," meaning **all** objects should be **continuously updated** to ensure logical continuity and correctness.

If a tree falls in a forest and no one sees it, **does it truly need per-frame computation?**

Mathematical Equivalence

Stepwise evolution (traditional):

```
  t1: state1 = e(state0, Δt)
  t2: state2 = e(state1, Δt)
  t3: state3 = e(state2, Δt)
                ...
t100: state100 = e(state99, Δt)
      Cost: 100 computations
```

Compressed evolution (proposed approach):

```
t100: state100 = e(state0, 100*Δt)
              Cost: 1
      Computation Saving: 99%
```

If the results are **strictly identical** mathematically, why choose the expensive path?

Core Question：

Since **unobserved objects do not affect the observer's experience**, why compute their states continuously? If **per-frame integration** and **one-shot computation** are equivalent, why **waste resources** on stepwise evolution?

1.7 Proposed Solution: The Observer-Centric Paradigm

1.7.1 A Shift in Core Principles

- From **“the world exists objectively”** to **“the world is realized on demand.”**
- From **“objects evolve autonomously”** to **“evolution is triggered by observation.”**
- From **“global synchronous updates”** to **“localized, lazy updates.”**

1.7.2 The Key to Breaking the Trilemma

Under the traditional paradigm:

World scale × Content fidelity = Compute cost *(multiplicative relationship)*

Under the new paradigm:

World scale + Content fidelity = Compute cost *(additive relationship)*
↓
Compute only the observed portion (approximately constant).

Preview of key breakthroughs:

- **Dimensional Asymmetry Thesis:** leverage the fundamental differences between the real and the virtual.
- **Potential-State Concept:** a form of existence that consumes no ongoing resources until observed.
- **Two-Law System:** time mechanics that ensure causal completeness.
- **Compressed Evolution:** mathematically equivalent computational shortcuts.

Without a paradigm shift, technical limits will be reached and expectations for open worlds will remain unmet. Adopting an observer-centric paradigm makes it feasible to realize worlds **100× larger** on current hardware.

1.8 Principle of Minimal Computation

Core idea: compute only what is necessary under limited resources

- Skip computations that can be skipped.
- Compress processes that can be compressed.
- Defer updates that can be deferred.

This is a pragmatic choice, not an idealistic pursuit.

Elaboration: Imagine a hotel with 10,000 rooms. The traditional method is to clean every room every day, regardless of occupancy. What is the point? Cleaning rooms that no one occupies—and no one will occupy—is pure waste.

The proposed approach resembles intelligent hotel management:

- **During unoccupied periods:** a room stays in a *“cleanable”* state (a **potential state**) with no routine cleaning performed.

- **Upon receiving a reservation:** right before check-in, quickly compute the accumulated dust over the idle interval and perform a one-shot cleaning to bring the room up to standard.
- **Special-case handling:** if a mouse enters during the idle period (**Law II** intervention), the system registers a note such as *"Mouse detected at T5; extra disinfection required,"* and this is handled together before check-in.
- **Result guarantee:** at the moment of check-in, the room's state is fully correct—the expected cleanliness is achieved and flagged issues have been resolved.

The critical difference:

> **Traditional method:** clean **10,000** rooms every day, **9,900** of which are unoccupied → massive waste.
>
> **Observer-centric method:** clean only the **100** rooms about to be occupied → **~99%** work saved.

This is genuine efficiency—not neglecting to clean, but intelligently identifying **when** cleaning is necessary and performing **all required work at the right time** (immediately before occupancy).

1.9 Paradigm Comparison: Traditional World Model vs. Lazy-Update World Model

Feature	Traditional Game Architecture (Object-Centric)	This Theoretical Model (Observer-Centric)	Significance of Improvement
Core paradigm	Objects update autonomously	Updates are triggered by observation	Paradigm shift
Update mechanism	Each object exposes Update()	Objects have no autonomous update capability	Decoupled control
Trigger mode	Auto-invoked every frame	Triggered only when observed	On-demand computation
Computation strategy	Frame-by-frame accumulation	One-shot compressed evolution	Mathematical equivalence
Time model	Globally synchronized time	Per-object independent timelines	Temporal decoupling
Observer permissions	No distinction among observer types	Only **internal observers** can trigger updates	Privilege separation
Evolution process	Must be continuously simulated	Intermediate steps can be skipped	Process compression
Resource consumption	O(N × T)	O(K), with K ≪ N	Exponential optimization
Scale expansion	Performance degrades linearly	Performance nearly unchanged	Scale invariance
Design principle	Simulate reality	Minimize computation	Efficiency first
Mode of existence	Always in an actualized state	Predominantly in a **potential state**	Lazy existence
Dimensional relationship	Single-world viewpoint	Dimensional asymmetry	Dual frames of reference
LOD coordination	Rendering-only optimization	Logic + rendering, dual-layer optimization	End-to-end optimization

Inevitability of the Paradigm Shift:

Traditional "death spiral":

Bigger world → More computation → Higher cost → Fewer players → Project failure

Observer-centric virtuous cycle:

Bigger world → Same computation → Same cost → More players → Project success

Chapter 2: Core Concepts — Dimensional Asymmetry and Dual Frames of Reference

2.1 The Objective Difference Between Dimensions

Foundational fact: the external world (physical reality) and the virtual world inherently occupy different dimensions. This is not a design choice; it is an objective condition.

```
        Reality (the dimension inhabited by external observers)

                              |

        ──────── ESSENTIAL DIFFERENCE ────────    ← inherent and unbridgeable

                              |

           Virtual World (the digital dimension)
```

The core point here is to state a basic truth: the reality inhabited by external observers and the virtual world inside a computer exist in two fundamentally different, **non-crossable "dimensions."** The term *dimension* here does not refer to 2D/3D spatial dimensions, but to an ontological difference in the mode of existence.

Explanation:

- **Difference in the basis of existence.** External observers inhabit a physical world composed of atoms and governed by physical laws. Entities in a virtual world—no matter how photoreal they appear—are, in essence, digital data residing in memory and processors, governed by logic encoded in software. Between these two modes of existence lies a natural chasm that cannot be crossed.
- **Absolute separation of inside and outside.** The virtual world is an *internal* world with its own closed, self-consistent rule system. Reality, by contrast, is the *external* world. The virtual world can be understood as a self-contained universe; it cannot be entered directly the way one would walk into another room.
- **Interaction via a proxy.** Because of this objective dimensional difference, external observers (players or developers) cannot interact with the virtual world directly. Interaction must occur through a *proxy* or *interface* that senses and acts on their behalf. This proxy is the in-game avatar or controllable unit, or—in development tools—the camera. When keys, mouse, or controller inputs are issued, it is not the external observer reaching into the virtual world; rather, commands are sent to the proxy, which, as a member of the internal world, performs actions and perceives the environment. This mediated, proxy-based interaction is the most immediate manifestation of dimensional asymmetry.

2.2 Fundamental Differences in Observational Capability

2.2.1 Different Dimensions, Different Capabilities

Once **"current-state updates"** are bound to **"internal perception,"** two observer classes emerge with fundamentally different powers:

> **Internal observers:** *perceive → trigger update → see the current state.*
>
> **External observers:** *look → no update → see the potential state.*

Because reality and the virtual world occupy different dimensions, the two observer types differ in a decisive, unbridgeable way: **only internal observers hold the permission to trigger world-state updates.** This capability boundary is the crux of many seemingly "counterintuitive" phenomena.

Understanding dimensional asymmetry leads directly to the next insight: **what it means "to see" differs across dimensions.** The divergence in observational capability necessarily creates **two independent frames of reference**—an internal frame in which observation *actualizes and updates* state, and an external frame in which observation is *non-activating* and therefore reveals **potential** rather than **actualized** states.

This perspective is inspired by the core idea from Einstein's relativity—**measurement outcomes depend on the observer's reference frame** [78].

2.2.2 Core Capability Gap: the Presence or Absence of **`UpdateStateOnObserve()`**

Internal observers (e.g., NPCs or player-controlled avatars):

- **Possess the core capability:** their perception systems—vision, hearing, or other sensors—embed the `UpdateStateOnObserve()` function.
- **Perception triggers change:** "seeing" is an active, world-altering act. When an internal observer looks at an object, it immediately forces a **historical reconstruction** for that object, updating it from **potential state** to the **current state** consistent with the present time.
- **Experience:** within the internal observer's frame, everything is continuous and causally coherent. No object ever appears "paused" or "jumping," because each act of observation yields exactly the state that ought to exist.

External observers (e.g., developers or the human player outside the simulation):

- **Lack the core capability:** existing in the external (real-world) dimension, external observers do not have access to `UpdateStateOnObserve()`.
- **Viewing is reading:** "looking" (through an editor viewport or display) is passive data access only. What is revealed are backend data structures, evolution rules, and an object's **potential state**; the gaze cannot trigger any in-game logic update.
- **Experience:** the scene may appear "strange" or even "unscientific": the vast majority of objects remain in a quiescent **potential state**, and only when an **internal observer's** gaze sweeps over them do they instantaneously "snap" to the correct state.

2.2.3 Formation of Dual Frames: One World, Two Realities

The fundamental capability gap inevitably yields two entirely different observational outcomes for the *same* virtual world—thus forming **dual frames of reference**.

Internal frame (a causally continuous universe):

> From an NPC's vantage point, the world is perfectly self-consistent. In this universe, time flows continuously and the causal chain is intact. If a clock reads **1 o'clock** at **T=1**, then three minutes later—at **T=4**—looking again will necessarily show **4 o'clock**. All phenomena within this frame strictly obey the "physical laws" encoded in the codebase and the associated mathematical logic.

External frame (a discrete universe with "deferred computation"):

> From a developer's vantage point, the world appears discrete and "lazy." It is evident that, for the sake of extreme efficiency, the system omits all unnecessary intermediate steps. Objects are not truly "frozen"; they are **waiting to be computed**. The visible "jump" is precisely the moment when **lazy updates** and **compressed evolution** are triggered.

2.2.4 Seemingly Contradictory, Actually Unified

At first glance, the notion that an object is "both moving and stationary" appears to defy common sense. Once the concept of **reference frames** is introduced, the contradiction dissolves. This mirrors the essence of relativity: there is no absolute motion or rest—**everything depends on the observer's frame of reference**.

2.2.5 Dimensional Asymmetry ⇒ Capability Gap ⇒ Perceptual Divergence

> **External side lacks** `UpdateStateOnObserve()` **→ cannot update → sees the** *potential state***.**
>
> **Internal side has** `UpdateStateOnObserve()` **→ can update → experiences the** *current state***.**

Scene View (external frame) vs. Game View (internal frame) is the direct manifestation of this difference.

Concrete illustration in Unity:

> **Scene View:** reveals data and mechanisms; objects may appear motionless.
>
> **Game View:** presents the player's perspective; everything operates "normally."

The *same* world is rendered in two completely different ways. In this model:

> **For internal observers,** objects are always undergoing continuous evolution.
>
> **For external observers,** objects spend most of their time in a potential state (a computational quiescence).

Both descriptions are *real*—observers in different dimensions possess different capabilities and therefore obtain different observational outcomes. The phenomenon may look "strange," but it is not unscientific; it is a logically, causally, and mathematically sound engineering design created to achieve extreme performance. It is **not** a bug; it is the foundational "physics" of this virtual world. Objects always exist—the difference lies in **whether their state updates can be triggered.**

2.4 Duality of Existence: Current State vs. Potential State

Within this theoretical framework, an object's mode of existence is explicitly divided into two forms:

- **Current State**: the form in which an object's state at a specific moment is precisely computed and made manifest. This is a **compute-intensive** mode because the object must be activated, updated, and may participate in real-time interactions within the world.
- **Potential State**: the form in which an object fully exists—already present in the system's data structures—yet its *current* state is not being evaluated in real time. Instead, it is maintained as a *computable potential* in a dormant condition. In this mode the object consumes **no per-frame CPU update cycles**, and it is the default for most objects when they are not being observed.

Core design principle.
Objects always exist; what is on-demand is the *determinacy* of their current state, which is entirely contingent upon the perception of **internal observers**. Because **external observers** lack the capability to trigger state updates (the `UpdateStateOnObserve()` function), they can only perceive objects in their **potential state**.

2.4.1 Core Properties of the Potential State

The **potential state** is neither "non-existence" nor a "simplified existence." It is a well-specified, highly optimized mode of being with the following properties:

- **Completeness of data and rules.**
  When an object is in the potential state, all of its foundational attributes and its evolution rule—i.e., the evolution function `e`—are **complete and explicit**. The system knows exactly *what the object is* and *how it ought to evolve over time*; only the actual computation is **deferred**.
- **Lazy and passive computation.**
  The object does **not** possess an active `Update()` loop. It remains in **computational silence**, awaiting "awakening" by an **internal observer** equipped with sensors—typically via `UpdateStateOnObserve()`. This *on-demand computation* pattern is the cornerstone of the **principle of minimal computation**.
- **Logical continuity and process compression.**
  Although the potential state skips per-frame simulation across intermediate time points, the **causal/logic chain remains fully continuous**. When the object is observed and an update is triggered, the system performs **compressed evolution**—a one-shot computation that advances the state from the **last update time** to **now**. The result is **mathematically equivalent** to per-frame integration.
  Example: instead of simulating an apple's rotting process 100 times over 100 seconds, the system, upon observation, applies `e` once to obtain the apple's rot level at **t = 100 s**.
- **Chained state inheritance.**
  After each lazy update, the object records its latest state (`lastUpdatedState`) as the starting point for the next round of compressed evolution. This guarantees that the object's evolutionary history is **continuous and cumulatively maintained**, rather than being recomputed from the initial state each time.

2.4.2 The Complete Form of Existence: Beyond Point-in-Time Definitions

Taken together, this model extends "existence" from a state defined at a single instant to an integrated concept spanning **past, present, and future**. An object's complete existence is jointly defined as:

Existence = Data Structure + Evolution Function *e* + Prediction Line (if any) + History Record

- **Data Structure:**
  Defines the object's **static essence**—its foundational attributes and identity
- **Evolution Function *e*:**
  Specifies the object's **intrinsic dynamics over time**—how its state should evolve as time elapses.
- **Prediction Line (if any):**
  Generated under **Law II (Observer Intervention & Causal Chain Settlement)**, it encodes the **constrained future "destiny"** produced by external interventions.
- **History Record:**
  Reconstructible via Law I (Observer Effect & Lazy Update) at any time, it defines the object's **verifiable past trajectory**.

2.6 Relativity of Perceived Continuity

2.6.1 Different Dimensions, Different Percepts

Core principle. Internal and external observers reside in **different dimensions** and possess **different capabilities** (presence or absence of `UpdateStateOnObserve()`), which leads them to **perceive evolution continuity differently**.

2.6.2 Examples of Continuity Perception

Assume an object moves one cell per second along the path **a → b → c → d**.

Case 1: Internal observer samples every second

```
t = 1: perceives → triggers UpdateStateOnObserve() → sees
                           object at a

t = 2: perceives → triggers UpdateStateOnObserve() → sees
                           object at b

t = 3: perceives → triggers UpdateStateOnObserve() → sees
                           object at c

t = 4: perceives → triggers UpdateStateOnObserve() → sees
                           object at d
       Experience: continuous motion a → b → c → d.
```

Case 2: Internal observer samples only at the start and the end

```
t = 1: perceives → triggers UpdateStateOnObserve() → sees
object at a

t = 2, 3: no perception (object remains in potential state)

t = 4: perceives → triggers UpdateStateOnObserve() → sees
object at d
Experience: continuous motion a → d (the evolution function e
guarantees logical continuity).
```

Key point: The internal observer **cannot distinguish** these two cases, because each perception yields a **"correct"** result at the moment of observation.

External observer's perspective (watching the whole interval)

```
t = 1: sees UpdateStateOnObserve() being called

t = 2, 3: sees the object stationary in potential state (cannot
trigger updates)

t = 4: sees UpdateStateOnObserve() being called; the object
"jumps" to d
Perception: discontinuous jump a … d (no UpdateStateOnObserve()
capability).
```

Design-implied phenomenon: divergent continuity perception

- **Internal observer:** can trigger updates → computes the current state each time → **experiences continuity**

  1. Experiences **historical continuity** via **Law I (Observer Effect & Lazy Update)**
  2. Experiences **causal inevitability** via **Law II (Observer Intervention & Causal Chain Settlement)**
  3. Cannot sense the underlying **compressed computation** and **prediction** machinery

- **External observer:** cannot trigger updates → mostly sees **potential state → perceives discontinuity**

  1. Sees the **trigger moments** and **computation** of **Law I**
  2. Sees the **generation** and **revision** of predictions under **Law II**
  3. Understands the system's mechanisms but **cannot change** them

- **Both percepts are real:** they arise from **different capabilities in different dimensions**.

Deeper implication. "Reality" is **relative** here: for the **internal** observer, the world is **continuous** and **causally complete**; for the **external** observer, the world is **discrete** and its **mechanisms are visible**. Both views are **true**—they differ only by observational capability.

Chapter 3: The Solution — The Two Laws and the Time Mechanism

3.1 The Time Model — A Compressible Causal Ruler

In this model, time is **not** a continuously flowing river in the traditional sense. Instead, it is a **compressible ruler** used to measure and compute changes of state. The design ensures that no matter how long an object has been "ignored," its evolution can be computed **precisely and in one shot** the moment it is needed.

3.1.1 Main Time Loop: The Metronome of the Universe

The virtual world possesses an **absolute, never-ceasing main time loop**. This can be understood as the world's **cosmic time**—the ultimate reference against which **all events and state computations** are measured.

```
        // Main Time Loop: the world's reference time
float currentTime = Time.time;  // world (universe) time
```

This **reference timeline** serves as the baseline for the entire world.

3.1.2 Time Increment (**timeElapsed**): Measuring the Span of "Being Ignored"

At the heart of the model is the computation of the **time increment** `timeElapsed`.
Whenever an object is perceived by an **internal observer**, the system immediately computes the difference between the **current main time** and the object's **last update time** (`lastUpdateTime`).

Computation:

```
float timeElapsed = currentTime - obj.lastUpdateTime;
```

This increment represents the total duration during which the object was **"ignored"** (kept in potential state).

Core meaning: If `timeElapsed` equals **100 seconds**, it means that—**at this very instant**—the system must **make up** all the natural evolution that should have occurred **over the past 100 seconds**. Crucially, this is a **one-shot, compressed computation**, *not* 100 iterative per-second updates.

3.1.3 Independent Timeline for Each Object

To reconstruct history precisely, **each object maintains its own set of time attributes**:

- `creationTime` **(time of creation):** records the absolute **main-time** instant at which the object "was born."
- `lastUpdateTime` **(time of last update):** the timestamp when the object was **last observed and updated**. This is the key reference used to compute `timeElapsed`.
- `localTime` **(object-local time):** represents the object's own **"age"**—the duration that has passed **from creation to now**.

3.1.4 Worked Example: An Apple's "Ignored" Life Cycle

Assume the current main time is `currentTime = 1200`.

> At **t = 1100**, the apple was seen once by an NPC and its state was updated (`lastUpdateTime = 1100`).

The system immediately performs:

> **Ignored duration (**`timeElapsed`**):** `1200 - 1100 = 100` seconds.
> Based on this value, the system **in one shot** computes the rotting changes that would have occurred over those **100 seconds**, starting from the state at **t = 1100**.

In this way, **time becomes the key ruler** connecting the object's discrete state points, ensuring **logical continuity** across its life cycle while **minimizing computation cost**.

3.2 Evolution Function e & Prediction Function p — The Twin Engines of World Change

In this model, all state changes are driven by two core functions: the **evolution function** `e` and the **prediction function** `p`. The former is the **"scribe of history,"** responsible for **retrospecting** and **reconstructing** the past; the latter is the **"planner of destiny,"** responsible for **projecting** and **pre-allocating** the future.

3.2.1 Evolution Function e: The Retroactive Law of Natural Change (Core of Law I)

Purpose: `e` answers: **"For an object that has gone unobserved for a long time, what *should* it be like *now*?"** It is used to **make up** changes caused purely by the passage of time.

Definition & mechanism:

```
e(lastUpdatedState, timeElapsed) → currentState
```

- `lastUpdatedState` — The starting point for computation: the object's state **at the last moment it was observed and updated**. This timestamped state ensures **continuity** of evolution.*Example:* if an object was observed at **T10** and then again at **T25**, `e` computes the 15-second evolution **from the T10 state**, not from the initial state at T0.

- `timeElapsed` — The amount of time that has passed **since the last update**; this is the **driver** of natural evolution.
- `currentState` — The computed state the object **ought to have at the present moment**.

Generality： `e` is a general framework capable of encapsulating any logically coherent, time-continuous rule:

- **Physical laws:** e.g., height under gravity, heat generated by friction.
- **Biological laws:** e.g., plant growth, food decay, organism aging.
- **Game rules:** e.g., cooldown timers, resource respawn cycles.

Core idea： With `e`, the system **abandons costly per-frame numeric simulation** and instead obtains the end result via a **direct formula/closed-form (analytic) step**—a **compressed evolution** that dramatically improves efficiency.

3.2.2 Prediction Function p: The Forecasting Law of Causal Chains (Core of Law II)

Purpose： `p` answers: **"Once an unobserved object is acted upon by an observer's energy input, what chain of events will be triggered?"** It **budgets** the future event sequence caused by a specific **intervention** (the observer's energy).

Definition & mechanism：

```
p(currentState, energy, environment) → (nextEvent, newState,
                          remainingEnergy)
```

- **Inputs.** The object's **current state** plus an **energy input** (e.g., throw impulse, collision momentum) within a given **environment**.
- **Process.** `p` iterates **until the energy is exhausted**, thereby generating a **Prediction Line**—a sequence of **key event points**.
  Each event point records **time**, **event type** (e.g., collision, stop), the **state at that moment**, and the **remaining energy**.

Generality： Like `e`, `p` can implement any logically self-consistent causal rules; its essence is **energy transfer and transformation** along a causal chain, pre-allocating the object's **constrained future** as required by **Law II**.

3.2.3 Relationship between e and p: Two Sides of One Evolutionary Rule

Although **e** and **p** apply to different scenarios, together they construct a complete, logically self-consistent system of temporal evolution.

Aspect	Evolution Function e	Prediction Function p
Core role	Retrospect the past	Budget the future
Driving force	Perception by an internal observer	Intervention by an observer
Process form	Continuous natural evolution	Discrete sequence of events
Associated law	Law I: Historical reconstruction upon observation	Law II: Causal forecasting upon intervention

3.2.4 Why e and p Are General-Purpose

e and **p** represent the **rules of evolution themselves**:

- **Not limited to any specific rule type:** they may encode **physical**, **magical**, or **arbitrary** laws.
- **Composable/multimodal:** a single **e** can simultaneously account for gravity, wind, and magic.
- **Open to invention:** designers may define entirely **new** evolution rules.

This allows the virtual world to adopt **any** logically coherent scheme of change.

Shared design constraints

1. **Determinism:** identical inputs must yield identical outputs.
2. **Causal logic:** results must be reasonable—no paradoxes such as time reversal.
3. **Conservation compliance:** must respect the system's specified conservation principles (e.g., conservation of energy, mass).

3.2.5 Mini-Summary

e and **p** are two mathematical expressions of the world's "physics."

- **e** ensures that, even when no one is watching, the world can **naturally** evolve via compressed, on-demand computation.
- **p** ensures that any **interaction** yields a logically consistent and **predictable** future.

Working in concert, they maintain a world whose **causal chains remain intact** even when large portions of computation are **deferred and compressed**.

3.3 The Two Fundamental Laws

3.3.1 Two Sides of One System: Law I and Law II as Opposite Directions of the Same Temporal Evolution

```
Past  ←─────────────────────────  Present  ─────────────────────────→  Future
              Law I                                  Law II
       (retroactive rebuild)                  (forward prediction)
```

Cycle of operation:

```
Law I (upon observation):     Potential State  →  Current State   (historical
reconstruction)
       ↑                                                        ↓
       └────────────────────────────────────────────────────────┘
Law II (upon intervention):   Current State   →  Future Potential State (causal
pre-allocation)
```

Law I — from **potential** to **actual** via **catch-up computation**: it fills in the missed evolution when an internal observer perceives an object (compressed evaluation of the past).

Law II — from **intervention** to **destiny** via **pre-computation**: it allocates a constrained future by generating a prediction line (event sequence) when energy is applied.

Together, the two laws maintain a **logically self-consistent causal world**, even when large portions of computation are **deferred** and **compressed**.

3.4 Law I: Observer Effect & Lazy Update

Core concept.
Objects that are not being observed remain in the **potential state**. They are promoted to the **current state** only when perceived by an **internal observer**.

Core mechanism (pseudocode):

```
public void UpdateStateOnObserve(GameObject obj, float currentTime) {
    // 0) De-duplicate within the same frame
    if (currentTime == obj.lastUpdateTime) {
        return;  // do not recompute in the same frame
    }

    // 1) Compute time increment
    float timeElapsed = currentTime - obj.lastUpdateTime;

    // 2) Historical reconstruction via compressed evolution
    obj.currentState = obj.evolution(obj.lastUpdatedState,
timeElapsed);

    // 3) Persist the new state as the next starting point
    obj.lastUpdatedState = obj.currentState;

    // 4) Update timestamp
    obj.lastUpdateTime = currentTime;
}
```

Mechanism, step by step:

- **Same-frame de-duplication:** if multiple observers look at the same object in the same frame, compute only **once**.
- **Time-increment calculation:** determine how much time must be **"made up."**
- **Historical reconstruction:** use the **evolution function** `e` to compute the **current** state from the **last** state.
- **State persistence:** save the result as `lastUpdatedState` to serve as the starting point next time.
- **Timestamp update:** record the observation time to prepare for the next computation.

Key point — chained state updates.
Each update is based on the previous result, forming a **chain of evolution**:

Initial → 1st observation → 2nd observation → 3rd observation → …

- Each arrow represents **one compressed-evolution computation**.
- This guarantees **continuity** and **correctness** of state evolution.

Design characteristics:

- **Triggerable only by internal observers:** external observers **do not** have this function.
- **One-shot full evolution:** no matter how long it has been, compute everything **at once** when observed.
- **Same-frame de-duplication:** avoid redundant work.
- **Efficiency-first: minimize** computation.

Concrete example — a candle in a closed room, unattended for 1 hour:

- **Traditional method: 3,600** computations (once per second).
- **This method: 1** computation (upon entry, directly compute how much the candle has burned down)

3.5 Law II: Observer Intervention & Causal Chain Settlement

- **Core concept:** When an **internal observer** intervenes in the world (e.g., throws, collides, triggers an action), the system performs a **one-shot causal settlement of the future** so that the causal chain remains complete **after the object leaves observation**.
- **Core principle — when prediction is triggered.** Law II's prediction does **not** start at the exact instant of the intervention. It is triggered at a **precise moment**: **when an object carrying "intervention energy" exits the field of view of all internal observers**.

1. While the object **remains observed**, Law I's `UpdateStateOnObserve()` ensures continuous motion.
2. Only **after the object leaves view** and enters the **potential state** does **Law II** take over, **generating predictions** to maintain causal logic.
   This clear division of responsibility prevents overlap between the two laws and directly embodies the **principle of minimal computation**.

Design inspiration — Event-Driven Programming[79].

- Convert future causal outcomes into **events**
- **Register** them with a scheduler and wait for triggers
- **Auto-execute** when their scheduled time arrives
- **Support modification/cancellation** of pending events

Core mechanism (pseudocode)

```
// Triggered when an intervened object leaves all internal observers'
viewvoid OnObjectLeavesObservation(GameObject actor, Action action,
float currentTime) {
    // 1) Analyze the intervention's energy and its target
    Energy energy = action.GetEnergy();
    GameObject target = action.GetTarget();

    // 2) Use prediction function p to compute the complete causal
chain
    PredictionLine predictionLine = PredictOutcomes(target, energy,
currentTime);

    // 3) Transform the prediction line into a sequence of future
events
    List<FutureEvent> events = predictionLine.ToEvents();

    // 4) Register events with the central causal scheduler
    foreach (var ev in events) {
        CausalScheduler.Register(ev);
    }

    // 5) The target enters potential state, carrying its prediction
line
    target.EnterPotentialState(predictionLine);
}
```

```
// Prediction via p: given current state and input energy, forecast
futurePredictionLine PredictOutcomes(GameObject obj, Energy energy,
float startTime) {
    PredictionLine line = new PredictionLine();

    // p is analogous to e, but specialized for forecasting future
events
    State currentState = obj.GetCurrentState();

    while (energy.IsActive()) {
        // Predict the next key event
        NextEvent next = p(currentState, energy, environment);

        // Add a constraint (settlement point) to the line
        line.AddConstraint(next.time, next.eventType, next.state);

        // Update state and remaining energy
        currentState = next.state;
        energy = next.remainingEnergy;

        // Stop if energy is depleted or the state has stabilized
        if (energy.IsDepleted() || currentState.IsStable()) {
            break;
        }
    }

    return line;
}
```

Mechanism explained:

- **Forecast the entire causal aftermath.** Use p to compute the full sequence of events triggered by the intervention.
- **Register a memo.** Convert predicted events into **"future commitments"** and register them with the scheduler.
- **Enter potential state.** The involved objects **no longer require continuous computation**, awaiting event triggers instead.
- **Event-driven execution.** When time arrives, the scheduler **automatically fires** the corresponding events.

3.5.1 Three-Layer Structure of the Prediction Line

A **prediction line** is not a mere recorded path. It is a highly optimized, three-layer composite that concretizes an abstract "destiny" into computable data:

1. **Mathematical function (the "soul").**
   At its core, the prediction line is a mathematical formula describing the object's motion (e.g., a projectile equation $P(t) = P_0 + V_0 \cdot t + ½g \cdot t^2$) By storing only the initial parameters (e.g., P_0 , V_0 , etc.), the system can compute the exact state at any time **t**.
   Storage cost is **O(1)**—independent of trajectory duration or complexity.
2. **Causal convergence points (the "skeleton").**
   From the initial computation, the system identifies all **key causal events** along the path (e.g., **hit wall**, **land**, **stop**) and marks them as a time-ordered set of **convergence points** $C = \{(t_1, Event_1, State_1), (t_2, Event_2, State_2), ...\}$ These points form the **backbone** of the causal chain and are the core items the **event scheduler** must handle.
   Example: a convergence point might be **{T+2.5s, hit wall, rebound}**.
3. **Computation strategy (the "implementation").**
   In engineering practice, the system does **not** simulate frame by frame. It uses optimizations such

as **piecewise-linear approximation** and efficient queries (e.g., **SphereCast**) **between convergence points** for collision checks, achieving **precise prediction** at very low cost.

3.5.2 Idempotency and Reuse Principle of Prediction

Law II achieves extreme efficiency through a key mathematical property—**idempotency**.
Given the **same initial conditions** (intervention energy, initial state, environment parameters, etc.), the prediction function **p** will **always** produce the **same** result: the **same prediction line**, no matter how many times it is invoked.

Full scenario after a ball is thrown

- **T0:** ball is thrown
- **T1:** ball inside view → `UpdateStateOnObserve()` every frame
- **T2:** ball leaves view → **generate prediction line** L_1 (**one-shot**)
- **T3:** no observation → L_1 remains **valid**
- **T4:** observer **B** sees the ball → **query** `L₁ + UpdateStateOnObserve()`
- **T5:** B looks away →L_1 still **valid** (no re-prediction)
- **T6:** observer **C** sees the ball → **still** query L_1
- **T7:** ball stops →L_1 has **fulfilled** its purpose

This seemingly simple rule is the ultimate expression of the **Principle of Minimal Computation** in Law II and leads to the following **reuse policies**:

- **Predict once, reuse forever (until conditions change).**
  Generating a prediction line is a **one-shot, high-value** computation.
  Therefore the system calls **p only once**—when an energy-carrying object **first** leaves the observation of **all** internal observers.
  Thereafter the prediction line is **stored and reused**. No matter how many observers, at how many different times, intermittently observe the object later, the system **does not** recompute prediction. It simply **queries** the existing line to obtain the state at the requested time.
- **New intervention → new prediction.**
  A prediction line represents a **settled destiny** that changes **only** when a **new, effective intervention** alters the original causal chain.
  Thus, **only** if a **new intervention** occurs (e.g., placing an obstacle in the ball's path, kicking the ball again) will the system **invalidate** the old line and generate a **brand-new** prediction based on the new initial conditions.
  Mere **appearance or disappearance of observers** does **not** trigger a new prediction.

3.5.3 Progressive Prediction: A Compute-Load Optimization Strategy

When forecasting a **long, complex causal chain** (e.g., a fast-spinning ball rebounding dozens of times inside a closed room), computing the **entire prediction line in one shot** can create a CPU spike and cause stutter. **Progressive Prediction** addresses this by decomposing a single global prediction into a **sequence of schedulable segment predictions**.

1) Core Concept: Causal Convergence Nodes

To segment prediction, we first define the boundary of each segment—called a **causal convergence node**.

Convergence set：

$$C = \{(t_1, Event_1, State_1), (t_2, Event_2, State_2), ..., (t_n, Event_n, State_n)\}$$

Node properties：

- **Temporal ordering:** $t_1 < t_2 < \ldots < t_n$
- **Causality:** each event **changes** the system state
- **Energy non-increase:** $E(t_{i+1}) \leq E(t_i)$

- **Definition.** A causal convergence node is a **deterministic future event** on the prediction line that **significantly alters** the object's state or energy—most commonly, a collision.
- **Role.** Each node is both the **end of the previous segment** and the **start of the next**. Think of it as a waypoint that says: "Up to here, the first causal segment is settled; from here on, prepare to compute the next."

Examples:

```
{T+2.5s, hit wall, rebound}

{T+3.1s, hit ground, bounce}

{T+5.0s, stop, rest}
```

2) Computation Strategy (Implementation)

Piecewise linear probing:

```
segments = Ceil(totalTime / timePerSegment)
```

- **Choose a prediction horizon & segment count.**
  For example, target a 2-second horizon with 5 segments.
- **Compute precise waypoints.**
  Using the closed-form motion `P(t)`, evaluate the **exact** spatial point at each segment end (e.g., `Point1 = P(0.4)`, `Point2 = P(0.8)`, ...).
- **Perform segment casts.**
  From the previous node to the current waypoint, run a **SphereCast** (or similar) to test the path.
  If a collision is detected, **stop immediately**—the first **causal convergence node** for this segment is found.
- **Adaptive accuracy.**
  Make segment density **adaptive in time** (or curvature/velocity/energy): complex portions get **finer** subdivision; simple portions use **coarser** steps.

Strategy characteristics:

- **Exact trajectory points:** $P(t_i)$ are computed with the **precise formula**.
- **Approximate collision checks:** straight-segment **SphereCast** between nodes.
- **Adaptive refinement:** denser segmentation where dynamics are more complex.

3) Progressive Construction Pipeline

The prediction proceeds as a relay of small steps:

1. **Kick-off: compute only the first segment.**
   When **Law II** triggers, the system **does not** compute the entire causal chain.
   It computes **up to the first convergence node** (e.g., first wall hit), **registers** that node, and **defers** subsequent computation.
2. **Pre-fetch the next segment as time approaches the node.**
   A scheduler monitors world time. As the main clock **approaches** the first node (e.g., **0.5s early**), it enqueues the task **"compute segment 2."**

3. **Relay computation.**
   Before the first node actually occurs, the system uses spare CPU to finish the prediction from **node 1 → node 2**.
4. **Repeat until exhaustion.**
   The cycle **(approach node → schedule compute → finish next segment)** repeats until energy is **exhausted** and the object **stops**.

4) Key Advantages of Progressive Prediction

- **Load spreading:** A potentially **tens-of-milliseconds** monolithic compute becomes **multiple sub-millisecond** tasks distributed across frames, avoiding latency spikes and preserving smooth gameplay.
- **Dynamic adaptability:** Because prediction is segmented, the system adapts better to **mid-course changes**.
  If a **new intervention** occurs on segment 3 (e.g., a newly placed obstacle), there is **no need to discard the entire long prediction**—recompute **only from the last settled node** onward.
- **Ultimate resource optimization:** Frequently, the **entire** causal chain never needs to be computed.
  If, say, the ball is **caught after the second bounce** (a new intervention), segments 3–5 are **never** computed.
  The scheduler can also **tune look-ahead and priority** based on real-time CPU load—under pressure, compute **only the most urgent** upcoming segments first.

3.5.4 Prediction-Line Mechanism — Summary

A prediction line is not a trajectory; it is a chain of causal convergence.

```
Intervention ───→ Convergence 1 ───→ Convergence 2 ───→ ··· ───→ Terminal
point
t=1: hit wall       t=3: rebound                  t=5: stop
```

Each Convergence point = *(time, event, state)*

How a prediction line is generated (upon observer intervention, e.g., a thrown ball):

1. **Analyze** the intervention's **energy** and **direction**.
2. **Compute** the complete **physical path** (closed-form where possible).
3. **Identify key event points** (collisions, stop, etc.).
4. **Produce** the **prediction line** and **register** it with the **scheduler**.

3.5.5 Dynamic-Revision Mechanism — Summary

Core principle: Time is one-way, but predictions are revisable.
When a **new intervention** occurs, the system performs a **causal-compatibility check** and updates the prediction accordingly.

Checks

1. **Temporal check:** Did the new intervention occur **before any already settled event** on the line?
2. **Spatial check:** Has the object's computed position **already passed** the intervention location?
3. **Causal check:** Have any **constraint points** along the line been **settled** (executed)?

Outcomes

1. **Fully valid → Generate a new prediction line** and **discard** the old one.
2. **Partially valid → Amend** the **unsettled portion** only.

3. **Invalid → Keep** the original prediction line unchanged.

3.5.6 Detailed Case Study: Base Scenario — Observer Throws a Ball, Then Stops Observing

Process breakdown

1. **Observer intervenes (throw).**
2. **Ball within view:** per frame, `UpdateStateOnObserve()` fires → motion appears continuous.
3. **Ball leaves view:** enters **potential state**, still carrying **intervention energy**.
4. **System detects energy → triggers Law II:** generates a **prediction line**.
5. **Prediction line** serves as a **causal memo**, awaiting settlement.

Case 1: Valid Intervention

Scene: Ball is expected to stop between 5–10 s. At **t = 6 s**, a sheet of cardboard is placed in its path.

```
Original line: ──────────────────────────────────────→ (10 s, natural stop)
                                    ↓
                         6 s: place cardboard
                                    ↓
New line: ────────→ (6.0 s, hit cardboard) → (6.5 s, rebound & stop)
```

Outcome: The ball hits the cardboard at **6.0 s** and rebounds, stopping at **6.5 s**.

Case 2: Invalid Intervention

Scene: Ball is expected to stop at **10 s**. At **t = 9 s**, cardboard is placed, but the ball **passed that point at 8 s**.

```
Original line: ───────────────────────────────────────────→ (10 s, stop)
                                                      ↑
                                         ball passed here at 8 s
                                       9 s: place cardboard (invalid)
```

Outcome: Keep the **original prediction line**; the ball stops at the originally predicted location/time.

Case 3: Intervention Then Revocation

A) Settled → revocation has no effect

```
6 s: place cardboard → 7 s: ball hits cardboard (settled) → 8 s: remove cardboard
                                             ↑
                                   too late (fait accompli)
```

Outcome: Collision already **settled** at **7 s**; removing the cardboard at **8 s does not** change history.

B) Unsettled → revocation is effective

```
6.0 s: place cardboard → 6.5 s: remove cardboard → 7.0 s: ball passes
    ↑                           ↑
  new line created        original line restored
```

Outcome: The ball proceeds along the **original path** as if the cardboard **never existed**.

3.5.7 Information-Selection Mechanism

Managing multiple prediction lines

Priority of information

Info 1: original prediction line (no intervention)

Info 2: intervention-derived prediction line (with intervention)

Info 3: revised prediction line (after revocation or new intervention)

Selection rules

- **Most recent valid** prediction line takes precedence
- **Not contradicted** (i.e., not invalidated by later facts)
- **Settled portions are immutable** (already executed events cannot be changed)

What the system does upon observation

1. **Query** all relevant prediction lines.
2. **Select** the **currently valid** line given the latest interventions/revisions.
3. **Compute** the object's current state **based on the selected line**.
4. **Present** the correct observation result.

Design principle. At the moment of intervention, the system **computes and schedules** all relevant causal consequences—much like **"searching the game tree"** in chess: we don't physically execute every move; we **mentally project** the outcomes.

3.6 Synergy of the Two Laws

Scenario: Observer **A** throws a ball; observer **B** observes later.

T0 — A throws the ball (Law II)

- Generate **predicted path and outcome**
- **Register** the event chain
- Ball **enters potential state**

T1–T4 — No observation

- Ball remains in **potential state**
- **No computation** occurs

T5 — Event fires: "hit wall"

- Update wall's state (if required)
- Ball **remains** in potential state

T7 — B observes the ball (Law I)

- Call `UpdateStateOnObserve(ball, T7)`
- **Query** the prediction line and compute the ball's position at **T7**
- Ball **appears** at the correct position

T8 — Event fires: "vase shatters"

- Vase's state changes
- **Spawn** fragments (if applicable)

T10 — Event fires: "ball lands"

- Ball's **final position** is determined

Key understanding

- **Law I** handles **"what happens upon observation"** (looks **to the past** via historical reconstruction).
- **Law II** handles **"what to predict upon intervention"** (looks **to the future** via causal pre-allocation).

Together they maintain a **complete causal chain**.

Energy carried by the object while unobserved is **saved** in the form of a **prediction line** during the potential state.

3.7 Guarantee of Causal Completeness

The system enforces a foundational principle:

3.7.1 At any moment, every object has a complete causal explanation

- Either **retrospect** its history via **Law I**
- Or **pre-know** its future via **Law II**

The two operate in **cycle**, forming an unbroken causal chain

3.7.2 Duality of observation and intervention

- **Observation:** turns an **unknown past** into a **determinate present** (**Law I**).
- **Intervention:** turns an **open future** into a **pre-committed destiny** (**Law II**).

This yields a form of **correctable determinism**: the future is **determined** (by predictions), yet **can still be altered** by new interventions **until** it becomes the past.

Chapter 4: Empirical Proof & Future Outlook

4.1 Scaling Effect

Scaling effect and scale invariance. As the virtual world grows, the performance advantage of lazy updates amplifies—often described as *exponential* in practical terms. Evidence comes from the clock test in the **"Strangest Experiment"** comparison:

- **Traditional architecture.**
  Suppose the world contains **N** clocks that must be updated independently. Each frame, the system executes one update on **all N** clocks. Compute cost ∝ **N**. When **N** grows from **100** to **10,000**, CPU load grows **100×**, and performance degrades sharply.
- **Lazy-update model.**
  The world still has **N** clocks, but at any instant there are only one or more **internal observers**. Due to view frustum and viewing distance, the number of clocks they can *simultaneously* observe—call it **K**—is tightly bounded, and **K** remains essentially unchanged as **N** increases. Therefore, per-frame updates ≈ **K**. When **N** goes from **100** to **10,000**, as long as observers' views are similar, total computation remains **nearly constant**.

This **scale invariance** is a core advantage of the model. In principle, developers can build worlds with **millions or tens of millions** of dynamic entities while keeping the **core logic compute** at a relatively **flat, low** level. This breaks the traditional linear trade-off between world size and performance. *(For detailed mathematical derivations, see Part 2; for empirical validation, see Part 3.)*

Why is K effectively constant?

1. **Field-of-view limits:** observers have finite frustum and range.
2. **Occlusion culling:** walls and terrain block many objects from being seen.
3. **Attention limits:** even within view, an observer can focus on only a limited set.
4. **Physical limits:** no observer can see all corners simultaneously (blind spots exist).

Scaling advantage when the world grows from 100 → 10,000 entities:

- **Traditional approach:** performance degrades by **100×**.
- **Lazy update:** performance is **nearly unchanged**.

Bottom line — Scale invariance: no matter how large the world becomes, the system **only computes what is observed**.

4.2 Critical Appraisal & Design Trade-offs

Despite the enticing prospects, a flawless implementation of this model forces developers and teams to confront—and accept—serious challenges and costs on **three fronts**:

1) A sharp rise in design complexity

This model shifts much of the computational burden **from runtime machines (CPU/GPU)** to **design-time humans (brains/tools)**.
Under traditional architectures, behavior can be expressed with simple iterative logic inside `Update()` (e.g., `position.y -= gravity * deltaTime`).
In the new model, for **every** dynamically evolving object, developers must craft **mathematically well-defined and efficient** functions: the **evolution function** `e` and the **prediction function** `p`. This demands a shift from **procedural, discrete simulation thinking** to **analytic, continuous function thinking**.

For complex, nonlinear, multi-body interactions (e.g., high-fidelity fluids, dense crowd dynamics, chaotic weather systems), producing `e` and `p` that are *both* correct and comprehensive can be extremely difficult. Teams will need **stronger mathematics and physical-modeling capability**.

2) Disruptive reconstruction of traditional architecture

This model is **not** a drop-in "plugin" or "middleware" for existing engines. Its core ideas—**observation-triggered updates, lazy computation, and event-driven causal chains**—fundamentally conflict with frame-centric synchronous update loops in mainstream engines. Realizing the model requires **overhauling** the game loop, object management, and time systems at the **core runtime level**.

That implies **significant engineering effort and technical risk**. For teams with mature pipelines and large codebases, the **migration cost can be very high**.

3) A fundamental shift in debugging paradigms

Introducing **potential state** and **prediction lines** brings new debugging challenges. Traditional debuggers excel at pausing on a specific frame and inspecting every object's *current* state. Under this model, that approach may fail:

- **How to visualize a potential state?**
  For an object in potential state, a "current state" does not exist conceptually. What should a debugger display?
- **How to trace and validate a complex prediction line?**
  Developers will need tools to visualize a future causal chain with dozens of constraint points and verify its logical correctness.
- **How to reproduce bugs triggered only under specific observation conditions?**
  An error might originate from a flawed e that, after hours in potential state, yields a catastrophic deviation when finally observed. Tracing bugs **after time compression** is far harder than in traditional workflows.

In summary, the model's central trade-off is clear: it demands **substantial upfront intellectual and engineering investment** in exchange for **unmatched runtime performance**. This trade-off dictates where the model fits best. It is particularly suitable for worlds with **clear, predictable laws** (e.g., spaceflight/orbital mechanics, physics-puzzle games), where e and p are relatively straightforward to define. For systems rich in **chaos and complex emergence**, the design cost and logical risk may become prohibitive.

Adopting this model requires teams not only with strong engineering skills, but also with **deep systems design sense and mathematical-modeling expertise**.

4.3 Future Outlook & Synergy with LOD

This model is **not** a replacement for existing optimizations. On the contrary, it **pairs perfectly** with them—especially **LOD (Level of Detail)**—to form an unprecedented **two-layer optimization**:

- **Lazy Update (logic-layer optimization).**
  Optimizes **game logic**. For **unobserved** objects, skip logic updates entirely (keep them in the **potential state**). For **observed** objects, perform a **one-shot compressed evolution** only at the moment of observation. Net effect: a **large reduction in CPU-side logic work**.
- **LOD (rendering-layer optimization).**
  Optimizes **graphics**. Based on object–camera distance, render with different **model/texture fidelities**. Net effect: a **large reduction in GPU load**[45][46][10][21].

Key idea: these act at **different stages** of the pipeline and **complement** each other, producing an **end-to-end** optimization from logic to rendering.

4.3.1 Scenario: A City Block with 10,000 Objects

1. **9,000 fully invisible objects** (inside buildings, outside the frustum, or fully occluded)

   - **Lazy update:** remain in **potential state → zero** logic cost.
   - **LOD/Culling:** outside frustum or occluded → **do not enter** the render pipeline → **zero** rendering cost.

2. **800 distant, visible objects**

   - **Lazy update:** upon observation, do **one compressed evolution**.
   - **LOD:** render with **lowest fidelity** (e.g., **LOD2/HLOD**) and **low-res textures** → very low GPU cost.

3. **150 mid-range, visible objects**

- **Lazy update:** upon observation, do **one compressed evolution**.
- **LOD:** render with **medium fidelity** (**LOD1**) and standard textures → moderate GPU cost.

4. **50 near, visible objects**

- **Lazy update:** upon observation, do **one compressed evolution**.
- **LOD:** render with **highest fidelity** (**LOD0**) and high-resolution textures → higher GPU cost (but for very few objects).

4.3.2 Combined Advantage

- **Logic compute.**
  Compared with a traditional architecture that might **tick thousands of active objects per frame** (even when off-screen), the lazy model reduces this to **one-shot compressed updates** for only the ~**1,000 observed** objects. CPU load drops by **orders of magnitude**.
- **Rendering load.**
  Instead of potentially rendering **~1,000 high-fidelity models**, the pipeline **tiers** the work (**50 high + 150 medium + 800 low**). GPU load is **significantly** reduced.

Multiplicative effect.
In traditional setups, even with advanced mesh virtualization like **UE5 Nanite** that handles massive polygon counts, the **CPU main thread** can still bottleneck on **logic/animation/physics** for many objects. By shifting logic from **O(N)** to **O(K)** (only what's observed), the lazy model **relieves the main-thread bottleneck**. The freed CPU budget can go to **richer AI**, **finer physics** (for **observed** objects), or supporting **more draw calls**, allowing **LOD, Nanite**, and other rendering tech to **fully realize their power**.

4.4 Unified Vision: A Trinitarian Synergy

An ideal integrated architecture gives each pillar a clear mandate—much like a macro-scale **Model–View–Controller (MVC)** pattern in software engineering:

- **Genie 3 (Creator / Model).**
  From text/image prompts, it generates interactive environments **on demand**, and can maintain coherence over longer, real-time interaction horizons. *(DeepMind describes Genie 3 as its first real-time interactive world model; Genie / Genie 2 laid the groundwork for the "playable worlds" paradigm.)* [74][75][76]
- **Lazy-Update World Model (Simulator / Controller).**
  Executes **deterministic, real-time logic** over the objects produced by Genie 3. It manages object state transitions, interactions, and causal relations—the **controller** that drives world evolution.
- **Advanced LOD (Presenter / View).**
  With **Nanite / World Partition + HLOD / occlusion culling / Work Graphs**, it regularizes the submission of visible detail to the GPU: render only **perceptible geometry**, use hierarchical proxies to reduce draw calls, and leverage GPU-driven work graphs to increase throughput for small batches. [10][46][45][18]

This layered architecture clarifies responsibilities and, in principle, lets each component operate at its highest potential.

Technology Stack Component	Primary Function	Data Representation	Core Principle (Deterministic/Stochastic)
Lazy-Update World Model	Real-time logic simulation; causal-chain management	Structured game-object data	Deterministic
Advanced LOD	Real-time graphics &	Polygon meshes,	Deterministic

Technology Stack Component	Primary Function	Data Representation	Core Principle (Deterministic/Stochastic)
(Nanite / Work Graphs)	performance optimization	voxels, textures	
Genie 3	On-demand content generation; world initialization	Latent spaces / video streams	Stochastic

4.5 Synergy Potential of the Trinity: A Final Answer to the “Impossible Triangle”?

In theory, this fusion directly targets the three vertices of the “impossible triangle”:

- **Scale.**
  The lazy-update model’s **O(K)** complexity allows the **logic layer** to support effectively unbounded numbers of objects.
- **Fidelity.**
  Advanced LOD such as **Nanite** enables the **rendering layer** to handle vast geometric detail [46][18], while solutions like **Lumen** provide high-quality global illumination [77].
- **Cost.**
  Genie 3 can automate world and asset creation from natural-language prompts, potentially reducing traditional content-production **time and labor** by orders of magnitude. [75][76]

In such a setup, developers shift from heavy **builders** to higher-level **planners/conductors**. Instead of manually crafting every asset and placing every tree, they author **high-level rules and prompts** to guide AI in the foundational build, then focus human effort on **core gameplay** and **artistic expression**. This foreshadows deep changes in team size, skill composition, and even the day-to-day of creative direction.

4.6 Envisioned Experience: A Real-Time, Infinitely Scalable, and Dynamically Generated World

In an ideal future, a developer need only type: **“a cyberpunk city shrouded in eternal rain.” Genie 3** instantly generates the city’s macro layout, architectural style, and foundational assets. The **lazy-update world model** then takes over, simulating the daily lives of **millions of citizens**, the traffic of **flying cars**, and complex **physical interactions**. Finally, rendering systems such as **Nanite** and **Lumen** present all of this to the player in **cinematic quality**—in real time.
This is the ultimate form of the “explosive technological breakthrough” the user is seeking.

4.7 The Determinism–Stochasticity Dilemma: Reconciling Causal Laws with Generative Creativity

This is the **core conflict** within the fusion plan.

- **Determinism required by the lazy model.**
  The causal completeness of the lazy-update model **depends entirely** on the determinism of its **evolution function** e and **prediction function** p—for the **same inputs**, they **must always** produce the **same outputs**. This determinism underpins **gameplay design**, **network sync**, and **debugging**.
- **Genie 3’s inherent stochasticity.**
  Generative AI models are, by design, **stochastic (probabilistic)**. Even with **identical prompts**, successive generations may differ. This unpredictability fuels **creativity**, but it is a **fatal flaw** for game logic that demands **precise control**.
- **Point of conflict.**
  How can a **deterministic simulator** depend on a **stochastic generator** for **real-time interaction**?
  If the simulator needs a **“rock”** to run physics, but Genie 3 may produce a rock whose **shape,**

mass, and friction vary each time, then carefully authored **levels, physics puzzles, and behaviors** would **instantly break**. This fundamental contradiction makes it **impractical** to integrate Genie 3 **directly** into the real-time game-logic loop.

4.8 Bridging the Representation Gap: From Latent Space to Usable Game Objects

The second hard barrier is a **data-format mismatch**.

- **Genie 3's output: a pixel stream.**
  Public descriptions indicate Genie 3 produces an **interactive video stream**, *not* a set of discrete 3D assets with engine-ready attributes (collision meshes, material IDs, physical parameters, etc.). Its internal representation lives in a **latent space** that humans cannot directly interpret.
- **Lazy model's input: structured data.**
  The lazy-update world model operates on **well-defined, structured, discrete game objects**, so that the evolution function e and prediction function p can perform mathematical operations on them.
- **Why real-time translation is infeasible .**
  There is currently **no technique** that can, **within a 16 ms frame budget**, reverse-engineer Genie 3's video or latent representation into **millions** of engine-ready objects with clean topology, correct UVs, and explicit physical properties. This **representation gap** is a hard technical wall blocking direct real-time integration.

4.9 A Hybrid Model: Decoupling Content Generation from Real-Time Simulation

Assuming the Genie family cannot eliminate its inherent **stochasticity**, a pragmatic path is a **hybrid architecture** that **decouples content generation from real-time simulation** across the development lifecycle. This respects the differing technical needs of each phase.

- **Offline world generation (development phase).**
  During production, developers use **Genie 3** as an advanced **Procedural Content Generation (PCG)** tool. Through prompt engineering, they iteratively create vast worlds, distinctive assets, or level layouts. This can be **slow**, **curated**, and **designer-guided**.
- **Asset extraction & import.**
  Assuming future pipelines can convert Genie 3's outputs (or latent representations) into **standardized 3D asset formats**, those assets are then **imported** into a conventional engine.
- **Real-time simulation & rendering (runtime phase).**
  On players' machines, the **lazy-update world model** and **advanced LOD systems** (e.g., Nanite) take over these **now-deterministic** assets. The lazy model efficiently simulates massive object logic; LOD efficiently renders them.

This architecture **leverages each component's strengths** while **avoiding their real-time conflicts**: use **generative AI** to tackle the **Cost** vertex of the "impossible triangle," the **lazy-update model** to address **Scale** via **O(K)** complexity, and **advanced LOD** to sustain **Fidelity**.

Chapter 5: Conclusion

The **Observer-Centric Virtual World Model** offers a finely crafted—and genuinely revolutionary—theoretical answer to the worsening "**impossible triangle**" crisis in open-world development. Its core advantage is a fundamental shift in **what triggers computation**: from **default, per-frame updates** to **on-demand evaluation**. By doing so, it **decouples core logic complexity from total world size**, achieving a theoretical **scale invariance**. This leap to **O(K)** complexity is the key to breaking performance bottlenecks that have constrained the industry for decades.

At the same time, a critical appraisal makes the cost of this revolution clear. The model **moves complexity from runtime machines (CPU/GPU)** to **design-time humans and tools**. Teams must bring unprecedented levels of **mathematical modeling**, **systems architecture**, and **abstract thinking**. Implementation demands not just modifications but a **ground-up rework** of mainstream engine loops, alongside brand-new debugging paradigms and tools to cope with **potential state** and **prediction lines**.

Final verdict. This model is **not** a plug-and-play replacement for existing technology. It is better understood as a **future-leaning blueprint** suited to **specific domains**—for example, ultra-large-scale simulations with **deterministic** physical laws—built **from scratch** by highly specialized teams. Its present-day value lies not only in engineering potential but also in its **philosophical stance**: it challenges conventional notions of "reality" in virtual worlds and points the industry toward a path beyond legacy architectures—toward worlds of **truly open possibility**. In time, mainstream engines may gradually absorb elements of this approach, but realizing the **full** model will require substantial investment—a profound **engineering** and **cognitive** transformation.

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Appendix: Glossary (Extended)

- **Potential State**
  A mode in which an object fully **exists**, but its **current state is not being computed**. It retains complete data structures and evolution rules, yet consumes **no CPU for continuous updates**.
- **Compressed Evolution**
  An optimization that **skips intermediate steps** and directly computes the **final result**. It compresses many incremental calculations into **one step** while guaranteeing an **identical outcome**.
- **Sensor**
  A component that **turns an entity into an internal observer**. It can be a vision module, trigger, raycaster, etc., granting the ability to call `UpdateStateOnObserve()`.
- **External Observer**
  Us in reality—players, developers, testers. External observers **do not** have `UpdateStateOnObserve()`; they **only watch via the screen** and **cannot directly trigger** state updates inside the virtual world.
- **Internal Observer**
  An entity **inside** the virtual world that **has** `UpdateStateOnObserve()`, such as the player character, NPCs, or sensor-equipped cameras. Its **perception directly affects** world state.
- `UpdateStateOnObserve()`
  The **observation-triggered** state-update function. This is the **core** of the model and is **only callable by internal observers**—it converts a **potential state** into a **current state**.
- **Evolution Function** `e`
  Defines how an object evolves **over time**.

Input: `lastUpdatedState`, `timeElapsed` → **Output:** `currentState`.
Used by **Law I** for **historical reconstruction**; in essence, it is **energy evolution along the time dimension**.

- **Prediction Function** `p`
  Defines how an object evolves **by energy transfer**.
  Input: `currentState`, **energy input → Output: future event sequence**.
  Used by **Law II** for **causal forecasting**; in essence, it is **energy evolution along the event dimension**. Like `e`, it is **customizable** and follows the **same design constraints**.
- **Time Increment (**`timeElapsed`**)**
  The duration an object has been **"ignored."** The elapsed time since the last update, used to compute the **catch-up** evolution that must be applied.
- **Dimensional Difference**
  The fundamental difference between **reality** and the **virtual world**—not 2D/3D space, but a **difference in the plane of existence** and capabilities.
- **Causal Memo**
  The **predicted-and-registered future events**. When an observer intervenes, the system **forecasts** all consequences and **records** them, ensuring the **causal chain** remains complete. Inspired by **event-driven programming**.
- **Prediction Line**
  The sequence of **causal constraints** produced by an intervention. It is **not** a raw trajectory, but an ordered series of **(time, event, state) convergence points** that define the object's **future destiny**.
- **Dynamic Correction**
  The mechanism by which a **prediction line can be modified** by **new interventions before** settlement. It embodies **"correctable determinism"**—the future is determined, yet **can be changed** until it becomes the past.
- **Causal Compatibility Check**
  The validation performed when a **new intervention** occurs. It checks **time**, **space**, and **causality** to decide whether the intervention is **valid** and whether a **new prediction line** must be generated.
- **Convergence Point**
  A scheduled point on the prediction line at which an event is **executed**. **Once settled, it becomes immutable history.**
- **Information Selection**
  The mechanism for choosing among **multiple coexisting prediction lines**. The system selects the **latest, valid, and not-negated** line as the **current truth**.
- **Causal Prediction**
  The mechanism that **computes and schedules** the **entire causal chain** at the moment of **intervention**.
- **Event-Driven**
  The programming paradigm borrowed by **Law II**: **future causal outcomes → events → registered with a scheduler → auto-triggered when due**, avoiding continuous computation.
- **Main Time Loop**
  The virtual world's **time reference**—a **unified baseline** on which all time-related computations depend.
- **Shortcut**
  An efficiency-oriented optimization that **skips intermediate calculations**. It is **not** cutting corners; it is a **smart computation strategy**.
- **Scaling Effect**
  The phenomenon that the **performance advantage of lazy updates grows exponentially in practice** as world size increases. When objects grow from **N** to **10N**, traditional methods slow down **~10×**, while lazy updates remain **almost unchanged** because the observer's field of view is **always limited**.
- **Scale Invariance**
  Regardless of how large the world becomes, compute cost depends only on the number of **observed objects** `K` **(approximately constant)**, **not** on the total number `N`. This is the **core advantage** of the lazy-update model.
- **Causal Completeness**
  The guarantee that **at any moment, any object** has a **complete causal explanation**—via **Law I** (retrospective history) or **Law II** (foreknown future)—forming an **unbroken causal chain**.