The McGucken Principle as the Physical Foundation of the Holographic Principle and AdS/CFT: How $dx_4/dt = ic$ Naturally Leads to Boundary Encoding of Bulk Information

Null Surfaces, Expanding Light Spheres, and the Geometric Origin of Holographic Duality

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> *"More intellectual curiosity, versatility and yen for physics than Elliot McGucken's I have never seen in any senior or graduate student... Originality, powerful motivation, and a can-do spirit make me think that McGucken is a top bet"*
>
> — John Archibald Wheeler, Princeton's Joseph Henry Professor of Physics, on Dr. Elliot McGucken

Abstract

The holographic principle — the conjecture that the information content of a volume of space is encoded on its boundary, with degrees of freedom scaling as area rather than volume — is one of the deepest ideas in theoretical physics. Its most precise realization is the AdS/CFT correspondence, which equates a gravitational theory in an anti-de Sitter bulk with a conformal field theory on its boundary. Yet the holographic principle itself has no accepted physical derivation; it is motivated by black hole thermodynamics and string theory, but its geometric origin remains unexplained. This paper shows that the McGucken Principle — that the fourth dimension is expanding at the rate of c, $dx_4/dt = ic$ — naturally and directly leads to holographic duality. The McGucken Principle identifies null surfaces (expanding light spheres, or McGucken Spheres) as the fundamental carriers of physical information and quantum correlations. Quantum nonlocality, in this framework, is not "action at a distance" but the geometric fact that correlated events share a common null structure — the same McGucken Sphere, the same four-dimensional coincidence. This is structurally identical to the holographic principle's claim that bulk information is encoded on boundary surfaces: apparent three-dimensional nonlocality arises because the observer is projecting data that are local and coincident on a null boundary. The paper establishes that the expanding null surface is a genuine geometric nonlocality in six independent mathematical senses — as a leaf of a foliation, a level set of a distance function, a causal wavefront (Huygens), a Legendrian submanifold in contact geometry, a member of a conformal pencil, and most deeply as a null-hypersurface cross-section — and shows that this six-fold geometric identity is what makes holographic encoding possible: because the null surface is a single unified object with a common identity in all six senses, the data on it is highly constrained, reducing degrees of freedom from volume scaling to area scaling. In gravitational settings, the natural generalization of the McGucken Sphere is the conformal boundary of a curved spacetime, and the encoding of bulk correlations on that boundary is precisely what AdS/CFT formalizes. The paper traces a four-step chain from $dx_4/dt = ic$ to AdS/CFT, showing that

holographic duality is not an arbitrary discovery of string theory but a natural and structurally expected consequence of the expanding fourth dimension.

1. Introduction: The Holographic Principle Without a Physical Foundation

1.1 The holographic principle

The holographic principle, proposed by 't Hooft [1] and developed by Susskind [2], states that the maximum entropy (and therefore the maximum information content) of a region of space is proportional to its bounding area, not its volume:

$$S_{\max} = \frac{A}{4l_P^2}$$

where A is the area of the boundary and $l_P = \sqrt{\hbar G/c^3}$ is the Planck length. This bound was motivated by Bekenstein's discovery that black hole entropy is proportional to the area of the event horizon [3], and by Hawking's demonstration that black holes radiate with a thermal spectrum determined by the horizon geometry [4].

The holographic principle implies that a $(d + 1)$-dimensional gravitational theory is equivalent to a d-dimensional non-gravitational theory living on the boundary — a dramatic reduction in the fundamental degrees of freedom. The most precise realization of this idea is the AdS/CFT correspondence [5], which equates type IIB string theory on $\mathrm{AdS}_5 \times S^5$ with $\mathcal{N} = 4$ super-Yang-Mills theory on the four-dimensional conformal boundary.

1.2 The missing physical foundation

Despite its power and elegance, the holographic principle has no accepted physical derivation. It is motivated by black hole thermodynamics and by specific constructions in string theory, but the question "why should information be encoded on boundaries?" has no geometric answer in the standard framework. As Bousso [6] has emphasized, the holographic principle appears to be a deep constraint on quantum gravity that existing frameworks can state but not explain.

1.3 The McGucken Principle provides a physical motivation for holographic duality

The McGucken Principle — that the fourth dimension is expanding at the rate of c, $dx_4/dt = ic$ [7, 8, 9] — provides a geometric motivation for the holographic principle. The McGucken Principle identifies null surfaces as the fundamental carriers of physical information. Quantum correlations are not transmitted through the bulk; they are inherited from shared geometric identity on a common null surface (the McGucken Sphere). This is structurally parallel to the holographic principle's claim that bulk information is encoded on boundary surfaces.

This paper traces the chain from $dx_4/dt = ic$ to AdS/CFT in four steps, showing that holographic duality is a natural and structurally expected consequence of the expanding fourth dimension. A central step in the chain is the demonstration that the expanding null surface — the McGucken Sphere — is a genuine geometric nonlocality in six independent mathematical senses (foliation, level sets, caustics, contact geometry, conformal geometry, and null-hypersurface cross-section), and that this six-fold geometric identity is the physical mechanism that reduces degrees of freedom from volume scaling to area scaling — the essence of the holographic bound.

1.4 Scope and honesty about claims

It is important to be precise about what this paper claims and what it does not. AdS/CFT is a very specific conjecture — it equates type IIB string theory on $\mathrm{AdS}_5 \times S^5$ with $\mathcal{N} = 4$ super-Yang-Mills with gauge group $SU(N)$ — derived from a specific D-brane construction with a large-N limit, a specific 't Hooft coupling, and a specific internal manifold carrying Kaluza-Klein modes that fix the operator spectrum of the boundary CFT. This paper does not derive any specific dual pair. It does not supply D-branes, a gauge group, a 't Hooft coupling, or an internal manifold.

What this paper does claim is more modest and, we believe, more foundational: it provides a physical rationale — rooted in spacetime geometry rather than string theory — for why a consistent quantum theory of gravity should admit a lower-dimensional boundary dual where null/conformal boundary data encode bulk physics. It explains why nature prefers boundary encoding of bulk information, leaving the construction of specific dual pairs to the string-theoretic machinery that has already accomplished this. The relationship is: the McGucken Principle provides the geometric reason for holography; string theory provides the specific realizations.

1.5 Assumptions and main claims

The paper rests on the following assumptions and claims, explicitly separated into rigorous results and interpretive identifications:

Assumptions:

- **M1 (McGucken Principle).** $dx_4/dt = ic$; the fourth coordinate $x_4 = ict$ is a real geometric axis expanding at c.
- **A1 (Null-surface information).** All long-range information transfer relevant for holographic encoding is mediated by massless fields following null geodesics. This is physically motivated by the standard role of null infinity ($\mathscr{I}^+$) and horizons in GR/QFT.
- **A2 (Asymptotic reconstructibility).** The asymptotic state of a gravitational system, as seen by an external observer, is fully reconstructible from data on a suitable null surface (future null infinity, horizon, or conformal boundary). This connects to Bondi-Sachs formalism [13], Penrose's conformal compactification [14], and Bousso's light-sheet construction [6].

Claims (labeled by type):

- **Theorem (rigorous):** Given M1, photons are stationary in x_4 and confined to null surfaces. Their information content is encoded on the expanding McGucken Sphere.
- **Proposition (physical):** Given A1 and A2, the information content of a region of spacetime is encoded on its bounding null surface, with degrees of freedom scaling as area in Planck units.
- **Interpretation (heuristic):** In a spacetime with negative cosmological constant (AdS), the natural generalization of the McGucken Sphere is the conformal boundary, and the encoding of bulk information on that boundary as a conformal field theory is the content of AdS/CFT.
- **Interpretation (heuristic):** The Ryu-Takayanagi formula admits a geometric interpretation as counting independent null-surface channels through the minimal bulk surface.

The paper is transparent about which claims are rigorous results and which are interpretive identifications that connect the McGucken framework to existing holographic structures.

1.6 Relation to existing perspectives on holography

Approach	Where holography comes from	What is missing or open
't Hooft / Susskind [1, 2]	Black-hole entropy, Planck-scale counting	No underlying dynamical or kinematic cause for area scaling
Bousso [6]	Covariant entropy bound via light-sheet construction in GR	Assumes entropy bounds; does not explain why information lives on light-sheets
Maldacena / AdS/CFT [5]	Specific D-brane/string construction gives duality	Duality is postulated (conjectured), not derived from spacetime kinematics alone
McGucken (this paper)	Expansion of x_4 and null-surface primacy specify where information lives	Does not derive specific dual pairs or microscopic structure; provides kinematic/geometric origin for boundary encoding

The McGucken contribution is positioned as providing a kinematic and geometric origin for boundary encoding — the physical reason why null surfaces and conformal boundaries are privileged — while acknowledging that the specific realizations of holographic duality (the D-brane construction, the large-N limit, the operator-dimension matching) require the separate machinery of string theory.

2. Step 1: From the McGucken Principle to Null-Surface Primacy

2.1 The McGucken Sphere as the fundamental carrier of information

The McGucken Principle states that every point event in spacetime generates an expanding McGucken Sphere — a null hypersurface whose spatial cross-section is a sphere of radius $r = ct$ [7, 10]. Photons are stationary in x_4: all of their invariant four-speed c is carried by spatial motion, so proper time does not advance [7]. This means that photons — the carriers of electromagnetic information — live entirely on the null surface. Their "history" is encoded on the McGucken Sphere, not in the bulk volume.

The six-fold geometric characterization of the McGucken Sphere [11] establishes that its surface is a genuine geometric locality: all points on the expanding wavefront share a common identity as members of the same null-hypersurface cross-section (Section 4 of [11]). Quantum correlations between entangled particles are not transmitted through the bulk; they arise from shared membership on the same McGucken Sphere — from coincidence on the null surface [10, 11].

2.2 Information lives on null surfaces, not in the bulk

The McGucken framework identifies three key facts:

1. The physical motion of light defines null surfaces (McGucken Spheres) along which information propagates.

2. For photons, proper time does not advance; their entire history is encoded on the null surface $ds^2 = 0$.

3. Quantum correlations (entanglement) are naturally expressed when the null surface is treated as the fundamental geometric stage, and three-dimensional space is treated as a projection or shadow.

This is already a holographic viewpoint: the "true" geometric constraint sits on the null surface (the boundary of the future light cone), and extended three-dimensional dynamics is the unfolding or projection of data encoded there. The McGucken Equivalence — that quantum nonlocality is the three-dimensional shadow of four-dimensional coincidence on the null surface [12] — is, structurally, the same statement that holography makes: apparent nonlocality in the projected space arises from locality and tight constraints in the higher-dimensional or more fundamental geometric structure.

Once one accepts the McGucken Principle as fundamental, one is already regarding a lightlike boundary surface as physically primary for encoding correlations, and the "bulk" region (our familiar three-dimensional or $3 + 1$-dimensional view) as a derived or shadow description. This is precisely the conceptual move behind the holographic principle.

2a. The Null Surface as a Geometric Nonlocality: Six Independent Proofs

The claim that "information lives on null surfaces" requires more than a slogan — it requires a rigorous demonstration that the null surface is a genuine geometric object whose spatially separated points share a common identity. This section, drawn from the formal treatment in [11, 16a], establishes this claim in six independent mathematical frameworks. Together, these six proofs constitute the formal foundation for the holographic encoding that the rest of the paper develops.

2a.1 Foliation theory

The expanding McGucken Sphere defines a foliation of three-dimensional space: a family of nested 2-spheres $S^2(t)$ parameterized by time. Each sphere is a leaf of the foliation, and the entire family carries a well-defined transverse geometry. The wavefront at any moment is a single geometric object — a leaf — that separates space into inside/outside regions with sharp topological meaning. All points on the leaf share a common identity as members of the same leaf. For holography, this means: the data encoded on a leaf is a single, unified dataset, not a collection of independent local data at separate points.

2a.2 Level sets of a distance function

The wavefront is the level set $d(x) = ct$ of the distance function from the origin. Every point on the wavefront is equidistant from the origin — a metric locality that is geometrically canonical. For holography: the boundary data at all points on the wavefront has the same "distance" from the bulk source, and the encoding is uniform in the metric sense.

2a.3 Caustics and wavefronts (Huygens)

The wavefront is a caustic — the envelope of secondary wavelets from every point on the previous wavefront. This makes it a causal locality: the boundary between the region that has received the disturbance and the region that has not. For holography: the null surface is not just a geometric convenience but a causal boundary. Information inside the surface has been "received"; information outside has not. The boundary encodes exactly the causal content of the bulk, which is the physical substance of holographic encoding.

2a.4 Contact geometry

In the jet space with coordinates (x, y, z, t), the growing wavefront traces a cone that is a Legendrian submanifold of the contact structure. All points on the Legendrian share a common contact-geometric identity, defined by the contact distribution rather than by position alone. For holography: the boundary data has a structure that goes beyond position — it is organized by the contact geometry of the wavefront, which encodes directional and momentum information as well as spatial position.

2a.5 Conformal and inversive geometry

Growing spheres under inversion map to other spheres or to planes. The family of expanding wavefronts belongs to a pencil in the inversive/Möbius geometry of space — a conformal locality invariant under the conformal group. For holography: the boundary encoding is conformally invariant. This is directly relevant to AdS/CFT, where the boundary theory has conformal symmetry. The conformal invariance of the McGucken Sphere's pencil structure is the geometric precursor to the conformal symmetry of the boundary CFT.

2a.6 Null-hypersurface locality: the deepest answer

The five frameworks above identify the wavefront as a locality in progressively deeper senses: topological, metric, causal, contact-geometric, and conformal. But the deepest identification is Lorentzian. The growing wavefront (radius = ct) is precisely a null-hypersurface cross-section — the intersection of the light cone with a spacelike slice:

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2 = 0$$

This is the most fundamental geometric locality possible: it is causal, metric, and topological simultaneously. It is the boundary of the causal future of the origin point. Null hypersurfaces are causally extremal — they are the only surfaces on which signals propagate at the invariant speed c. Every point on the wavefront has the same causal relationship to the source.

For holography, this is the critical identification: the null hypersurface is the canonical boundary on which information is encoded because it is the surface of maximal causal reach. The Bekenstein bound, the Bousso light-sheet construction, and the conformal boundary of AdS all inherit their role from this null-hypersurface structure. The six geometric frameworks established here provide the rigorous mathematical foundation for treating the null surface as a genuine, unified geometric object — not just a collection of points that happen to be on the same light cone, but a single entity with a common identity in six independent mathematical senses [11, 16a].

2a.7 From nonlocality to holography

Because every point on the expanding wavefront shares a common causal locality in all six senses, a photon surfing the wavefront inhabits the entire sphere of nonlocality with equal geometric weight until a measurement event localizes it in three spatial dimensions [11]. This is quantum nonlocality — the photon is not at one point on the surface; it is on the entire surface, and its probability of being found at any point is uniform (by the uniqueness of the Haar measure on $SO(3)$, as established in [23]).

This quantum nonlocality — the shared geometric identity of all points on the null surface — is precisely what makes holographic encoding possible. If the null surface were merely a collection of causally disconnected points, each carrying independent information, there would be no reduction in degrees of freedom — the boundary would need as many degrees of freedom as the volume. But because the null surface is a single geometric object with a common identity in six senses, the data on it is highly constrained: the information at one point is correlated with (and partially determined by) the information at every other point on the same wavefront. This constraint is what reduces the degrees of freedom from volume scaling to area scaling — the essence of the holographic principle.

The McGucken Nonlocality Principle — that all quantum nonlocality begins in locality [10] — therefore provides the physical mechanism for the holographic bound: information scales as area because the null surface's geometric nonlocality constrains the data to be a single, unified, correlated dataset, not a collection of independent bits.

3. Step 2: From Flat Null Spheres to Curved Boundaries

3.1 The McGucken Sphere in flat spacetime

In flat Minkowski spacetime, the McGucken Sphere is the forward light cone of a point event — the set of all events satisfying $|\mathbf{x} - \mathbf{x}_0|^2 - c^2(t - t_0)^2 = 0$ with $t > t_0$. Its spatial cross-section at time t is a sphere of radius $c(t - t_0)$. This is the natural arena where quantum information is organized [7].

3.2 Promoting to curved spacetime: the conformal boundary

In standard general relativity, lightlike surfaces play the same structural role in curved spacetime as in flat spacetime — they are where asymptotic data is encoded: Bondi data at null infinity [13], the S-matrix at scri [14], and the Bekenstein-Hawking entropy on horizons [3, 4]. The natural "outer" surface of a curved spacetime is its conformal boundary — the surface where lightlike trajectories asymptote.

In a spacetime with negative cosmological constant — anti-de Sitter (AdS) space — the conformal boundary is a timelike hypersurface at spatial infinity. This boundary plays the same structural role that the McGucken Sphere plays in flat spacetime: it is where lightlike trajectories end, where global constraints are naturally expressed, and where the complete pattern of bulk correlations is encoded [5].

The promotion from flat to curved spacetime is: the McGucken Sphere (the light cone of a point event in Minkowski space) generalizes to the conformal boundary of AdS space (the asymptotic surface where all light cones terminate). In both cases, the null or boundary surface is where information lives.

3.3 Area scaling of information

The McGucken Sphere's information content scales as its area, not as the volume it encloses. This is because the photon — the carrier of information — lives on the surface (being stationary in x_4), not in the interior. The number of independent quantum states on the sphere at time t is proportional to the number of Planck-area cells on its surface: $N \sim A/l_P^2 = 4\pi(ct)^2/l_P^2$. This is the

Bekenstein bound — derived here as a geometric consequence of the fact that information carriers (photons) are stationary in x_4 and therefore confined to the null surface.

The holographic principle's area scaling is not a mysterious postulate — it is the geometric consequence of the McGucken Principle: information lives on the expanding null surface because the carriers of information (photons) are stationary in the expanding x_4.

4. Step 3: From Wavefront Dynamics to Boundary CFT

4.1 Bulk wave equations and boundary operator data

In AdS/CFT, bulk fields obey wave equations in the curved AdS background, and their boundary values (or fall-off behavior at the conformal boundary) act as sources for operators in the boundary CFT [5, 15]. Correlators in the CFT are generated by evaluating the bulk on-shell action as a functional of boundary data — a generalized least-action principle with boundary conditions.

The McGucken framework connects to this structure through the chain established in prior work [8, 9, 16]: $dx_4/dt = ic \rightarrow$ Huygens' Principle $\rightarrow$ path integral $\rightarrow$ wave equation $\rightarrow$ principle of least action. In the McGucken picture:

- Huygens-like propagation in the bulk (the iterated expansion of x_4) maps to the propagation of wavefronts from interior to boundary.
- The principle of least action — derived from the geometry of x_4's expansion [9] — determines which bulk configurations contribute, via stationary phase, to the boundary data.
- The eikonal equation — the bridge between wave optics and geometric optics [9] — connects Huygens' wavefront propagation (McGucken Spheres) to ray propagation (geodesics), which in AdS/CFT maps to the propagation of operator insertions and correlation functions on the boundary.

4.2 Conformal symmetry from the expansion of x_4

A conformal field theory — the boundary theory in AdS/CFT — has conformal symmetry: invariance under the group $SO(2, d)$ of conformal transformations. In the McGucken framework, conformal symmetry arises naturally from the expansion of x_4:

- The expanding McGucken Sphere belongs to a conformal pencil — a family of spheres invariant under the conformal (Möbius) group of inversive geometry [11]. This is the fifth of the six geometric frameworks establishing the wavefront's locality.
- The null surface $ds^2 = 0$ is invariant under conformal rescalings of the metric: $g_{\mu\nu} \rightarrow \Omega^2 g_{\mu\nu}$ preserves the null condition. Null surfaces are conformally invariant objects.
- The asymptotic boundary of AdS inherits a conformal structure from the bulk metric. The boundary theory's conformal symmetry is the symmetry of the null/conformal boundary on which the McGucken Principle encodes information.

Conformal symmetry on the boundary is not an arbitrary feature of string-theoretic constructions — it is the natural symmetry of the null surfaces that the McGucken Principle identifies as fundamental.

4.3 Entanglement entropy and extremal surfaces

One of the deepest results in AdS/CFT is the Ryu-Takayanagi formula [17]: the entanglement entropy of a region A in the boundary CFT equals the area of the minimal extremal surface in the bulk that is homologous to A:

$$S_{\text{EE}}(A) = \frac{\text{Area}(\gamma_A)}{4G_N}$$

In the McGucken framework, this result has a natural geometric interpretation. Entanglement is shared geometric identity on a common McGucken Sphere [10, 11]. The entanglement entropy of a boundary region measures the amount of shared wavefront identity between that region and its complement — i.e., how many independent McGucken Spheres connect the region to the rest of the boundary. The extremal surface γ_A in the bulk is the geometric locus where these connecting McGucken Spheres are most tightly constrained — the "bottleneck" of shared wavefront identity. Its area counts the number of independent null-surface channels connecting region A to its complement, in Planck units.

The Ryu-Takayanagi formula admits, in the McGucken framework, a geometric interpretation: the entanglement entropy is related to the number of independent null-surface channels (in Planck-area units) that thread through the minimal bulk surface connecting the boundary region to its complement. This interpretation is heuristic rather than derived — the standard derivation uses the replica trick in Euclidean quantum gravity [17] — but it provides a physical picture that complements existing "bit thread" and tensor-network interpretations of holographic entanglement.

5. Step 4: Nonlocality and Holography as the Same Phenomenon

5.1 The McGucken Equivalence as holographic encoding

The McGucken Equivalence [12] states that quantum nonlocality and relativity are two aspects of the same geometric fact: the expansion of the fourth dimension at c. Quantum nonlocality is the three-dimensional shadow of four-dimensional coincidence on the expanding null surface. Entangled particles are not "connected at a distance" — they share a common position on the same McGucken Sphere, and their correlations are the geometric consequence of that shared identity.

The holographic principle makes the same structural claim in gravitational language: what looks like "deep bulk" interactions — correlations between distant points in the interior of a gravitational system — can be completely rephrased as correlations on the boundary. Apparent bulk separations are reexpressed as intricate but local structures in the boundary theory.

These are two descriptions of the same pattern: apparent three-dimensional (or bulk) nonlocality arises because the observer is looking at a projection of data that are simple, local, or coincident on a higher-dimensional, null, or boundary structure. The McGucken Equivalence's "x_4-coincidence" is the same structural move as holography's "boundary encoding of volume information."

5.2 The chain from $dx_4/dt = ic$ to AdS/CFT

The complete chain is:

1. **McGucken Principle:** $dx_4/dt = ic$ and the fixed four-speed c make null surfaces (McGucken Spheres) the natural carriers of physical information and quantum correlations.

2. **Holographic mindset:** Quantum nonlocality is best understood as coincidence or locality on the four-dimensional null geometry; three-dimensional "nonlocality" is its shadow. This already embodies a holographic viewpoint: fundamental dynamics and correlations live on null or boundary surfaces; bulk behavior is emergent or projected.

3. **Curved spacetime generalization:** In gravitational theories, the natural generalization of the McGucken Sphere is the conformal boundary of a curved spacetime (e.g., AdS), where light rays and global causal structure focus. The conformal symmetry of the boundary is the symmetry of the null surfaces on which the McGucken Principle encodes information.

4. **AdS/CFT:** Encoding all bulk gravitational information on the conformal boundary as a quantum field theory — with conformal symmetry, operator-boundary-value correspondence, and entanglement entropy given by extremal surface areas — is exactly the content of AdS/CFT.

Once one fully adopts the McGucken Principle's geometric interpretation of quantum mechanics and relativity, a holographic duality like AdS/CFT is not an arbitrary coincidence discovered in string theory but a natural and structurally expected consequence of the expanding fourth dimension.

6. The McGucken Principle and Black Hole Entropy

6.1 The Bekenstein-Hawking entropy from x_4 expansion

The Bekenstein-Hawking entropy of a black hole is $S = A/(4l_P^2)$, where A is the area of the event horizon [3, 4]. In the standard framework, this formula is derived from the laws of black hole mechanics and from Hawking radiation. But the physical question — why should entropy be proportional to area rather than volume? — is answered by the holographic principle, which itself has no accepted derivation.

The McGucken Principle provides the derivation. The event horizon of a black hole is a null surface — a surface where $ds^2 = 0$. In the McGucken framework, null surfaces are where information lives, because the carriers of information (photons) are stationary in x_4 and confined to these surfaces. The entropy of a black hole is proportional to the area of its horizon because the horizon is the null surface on which the black hole's information is encoded. The number of independent quantum states (the entropy) is the number of Planck-area cells on the horizon: $S = A/(4l_P^2)$.

This is not a new calculation — it reproduces the Bekenstein-Hawking result. But it provides the geometric reason for area scaling: information lives on null surfaces because the expanding x_4 confines information carriers to those surfaces. Volume scaling would require information to propagate through the bulk — but in the McGucken framework, the bulk is the shadow, not the fundamental arena.

6.2 Hawking radiation as x_4 expansion at the horizon

Hawking radiation — the thermal emission from a black hole — arises because the vacuum state defined by a freely falling observer differs from the vacuum defined by an observer at infinity. In the McGucken framework, the horizon is a boundary where the local rate of x_4 expansion becomes singular: the gravitational redshift at the horizon is infinite, meaning that the x_4-advance rate (in the coordinates of a distant observer) approaches zero. Virtual particle pairs created locally at the horizon — fluctuations of the expanding x_4 — are separated by the horizon's causal structure, with one particle falling in and the other escaping as Hawking radiation.

This is the same mechanism that produces the Dynamical Casimir Effect for accelerating boundaries [18]: the disruption of the local x_4 expansion geometry converts virtual pairs into real particles. The Hawking temperature $T = \hbar c^3/(8\pi G M k_B)$ is the temperature associated with the x_4 expansion being "pinched" at the horizon.

7. Relationship to Other Approaches

7.1 Relationship to Jacobson's thermodynamic derivation of Einstein's equations

Jacobson [19] famously derived the Einstein field equations from the thermodynamic relation $\delta Q = T\,dS$ applied to local Rindler horizons, assuming the Bekenstein-Hawking area-entropy relation. The McGucken framework provides the physical substrate for Jacobson's derivation: the expanding x_4 is the geometric process that generates both the entropy (via phase-space expansion [20]) and the null surfaces (Rindler horizons) on which Jacobson's argument operates. Jacobson's result is a theorem of the McGucken framework.

7.2 Relationship to Verlinde's entropic gravity

Verlinde [21] proposed that gravity is an entropic force — that gravitational attraction arises from the tendency of systems to maximize entropy. The McGucken framework provides the physical mechanism: the expansion of x_4 drives entropy increase [20], and the gradient of x_4 expansion rate (which varies with gravitational potential) produces an entropic force that reproduces Newton's law of gravitation [22]. Verlinde's entropic gravity is a consequence of the McGucken Principle.

7.3 Relationship to 't Hooft's original holographic proposal

't Hooft [1] proposed the holographic principle by arguing that the number of degrees of freedom in a gravitational system should be bounded by the area of its boundary in Planck units. The McGucken framework explains why: because the expansion of x_4 at c confines the carriers of information (photons, stationary in x_4) to null surfaces, and the number of independent channels on a null surface scales as its area in Planck units. 't Hooft's bound is a theorem of the McGucken Principle.

8. Standard Notation: The AdS Metric and Null Geodesics

To connect the McGucken framework to the standard AdS/CFT machinery, we briefly state the relevant geometry in standard coordinates.

In Poincaré coordinates, the AdS_{d+1} metric is:

$$ds^2 = \frac{L^2}{z^2}\left(-dt^2 + d\mathbf{x}^2 + dz^2\right)$$

where L is the AdS radius and $z > 0$ is the radial coordinate, with the conformal boundary at $z \to 0$. In the McGucken framework, the Minkowski metric is written with $x_4 = ict$:

$$ds^2 = dx^2 + dy^2 + dz^2 + dx_4^2 = dx^2 + dy^2 + dz^2 - c^2 dt^2$$

Null geodesics in AdS satisfy $ds^2 = 0$. In Poincaré coordinates, a radial null geodesic satisfies $dz/dt = \pm 1$ (in units with $c = 1$, $L = 1$), meaning that null rays reach the conformal boundary $z = 0$

in finite coordinate time. This is the AdS analog of the McGucken Sphere: null geodesics emanating from a bulk point reach the boundary, and the boundary is where the null structure "terminates." In flat Minkowski space, the corresponding boundary is future null infinity $\mathscr{I}^+$ (Penrose's scri-plus [14]), and null geodesics reach it in infinite affine parameter. The AdS geometry, with its negative cosmological constant, "brings the boundary in" so that null rays reach it in finite time — making the boundary more accessible and the holographic encoding more tractable.

The conformal boundary of AdS inherits a conformal class of metrics from the bulk. In AdS_5, this boundary is four-dimensional with conformal symmetry group $SO(2,4)$ — the isometry group of AdS_5, which is also the conformal group of four-dimensional Minkowski space. This specific group structure is a property of the AdS_5 geometry, not of null surfaces in general. The McGucken framework provides the physical rationale for why null surfaces and conformal boundaries should be privileged (because the expansion of x_4 confines information carriers to null surfaces); the specific conformal group $SO(2,4)$ is then determined by the specific bulk geometry (AdS_5).

9. Objections and Replies

9.1 "Isn't this just philosophical relabeling of known holographic structures?"

No. The McGucken framework provides nontrivial derivations that the standard holographic literature does not: area scaling of information from null-surface confinement of photons (Section 3.3), the connection to entropy increase via the expansion of x_4 [20], the path-integral structure from Huygens expansion [16], and the Born rule from wavefront symmetry [23] — none of which start from string theory or black hole thermodynamics. The philosophical framing ("information lives on boundaries") is shared with 't Hooft and Susskind; the physical mechanism ($dx_4/dt = ic$ confines information carriers to null surfaces) is new.

9.2 "How do you know all relevant information carriers are confined to null surfaces?"

This paper focuses on asymptotic information and gravitational entropy, for which null boundaries (horizons, $\mathscr{I}^\pm$) are already known to play the central role. Massive fields propagate through the bulk and are not confined to null surfaces. However, the holographic bound — $S \leq A/(4l_P^2)$ — applies to the total entropy of a region, including contributions from massive fields, and is saturated by black holes whose information is encoded on the null horizon. The McGucken framework explains why the bound is set by the area of a null surface: because the expansion of x_4 organizes information on null structures. Massive fields contribute to the bulk interior but do not change the leading area law for the holographic bound.

9.3 "AdS is special; what about flat or de Sitter space?"

In flat Minkowski space, the McGucken Sphere's null-surface structure connects naturally to the Bondi-Sachs formalism [13] and to Penrose's conformal compactification [14]. The S-matrix — the observable in flat-space quantum gravity — is defined on $\mathscr{I}^+$ and $\mathscr{I}^-$, which are null surfaces. Recent work on "celestial holography" aims to construct a holographic dual for flat space by studying conformal field theories on the celestial sphere at null infinity. The McGucken framework is compatible with and provides a physical motivation for this program: the celestial sphere is a McGucken Sphere at null infinity.

In de Sitter space (positive cosmological constant), the relevant boundary is the cosmological horizon — a null surface whose area bounds the entropy of the observable universe. The McGucken framework applies directly: the cosmological horizon is a McGucken Sphere at the Hubble radius, and the entropy bound $S \leq A_{\text{horizon}}/(4l_P^2)$ follows from null-surface confinement. De Sitter holography remains an open problem in the standard framework; the McGucken Principle provides a geometric context for understanding why boundary encoding should apply there as well.

9.4 "The Ryu-Takayanagi formula is derived from the replica trick, not from null-ray counting"

This is correct, and the paper does not claim to derive the Ryu-Takayanagi formula from the McGucken framework. The formula's standard derivation uses the replica trick in Euclidean quantum gravity and has been generalized to quantum extremal surfaces (QES) that include bulk entanglement — structures with no direct analog in null-ray counting. What the McGucken framework provides is a physical interpretation of the formula: in Lorentzian terms, the minimal surface γ_A can be seen as the locus that extremizes the bottleneck of causal/entanglement connections between region A and its complement. The McGucken Sphere picture provides a geometric representation of those connections in terms of families of null surfaces. This interpretation is compatible with existing "bit thread" and tensor-network interpretations of holographic entanglement [17], which also describe flows or threads crossing minimal surfaces. The McGucken framework augments these interpretations; it does not replace the standard derivations.

9.5 "The large-N limit and gauge structure are absent — isn't this a fundamental gap?"

Yes. The McGucken framework does not contain a gauge group, a 't Hooft coupling, a large-N limit, or the specific D-brane construction that generates AdS/CFT in string theory. This is acknowledged in Section 1.4. The McGucken contribution is at a different level: it provides the geometric reason why a gravitational theory should admit a boundary dual, without specifying the microscopic details of that dual. The relationship is analogous to the relationship between thermodynamics (which states that entropy increases without specifying a microscopic model) and statistical mechanics (which provides the microscopic model). The McGucken Principle provides the geometric thermodynamics of holography; string theory provides the statistical mechanics.

It should be noted that the McGucken Principle also provides the foundational geometry underlying time and all its arrows and asymmetries, as well as the Second Law of Thermodynamics itself [20, 24a, 24b]. The expansion of x_4 at c drives entropy increase through phase-space growth [20], provides the physical mechanism for the thermodynamic, radiative, cosmological, causal, psychological, and nonlocality arrows of time [24a, 24b], and triumphs over the "Past Hypothesis" by providing a dynamical mechanism for entropy increase rather than merely assuming special initial conditions [8]. The same geometric expansion that underwrites holographic encoding also underwrites the Second Law — because both are manifestations of the same process: the irreversible, one-way expansion of the fourth dimension, which grows the accessible phase space (producing entropy increase) and confines information to null surfaces (producing area scaling). Holography and thermodynamics are two faces of one geometric fact.

9.6 "Aren't you claiming to derive what Maldacena himself presented as a conjecture?"

No. This paper does not derive AdS/CFT in the sense of constructing a specific dual pair, reproducing operator dimensions, matching correlation functions, or establishing the $1/N$ expansion on both sides. It provides a physical motivation — rooted in spacetime geometry — for why holographic dualities should exist and why boundary theories should have conformal symmetry. This is a different kind of contribution from Maldacena's, and a complementary one. Maldacena showed that a specific duality exists (conjecturally) and marshalled overwhelming evidence for it. This paper proposes why such dualities are geometrically natural, from a principle that also derives relativity, quantum mechanics, and entropy independently of string theory.

10. Conclusion

The McGucken Principle — that the fourth dimension is expanding at the rate of c, $dx_4/dt = ic$ — provides the physical foundation for the holographic principle and AdS/CFT. The chain is direct:

1. The expansion of x_4 makes null surfaces (McGucken Spheres) the fundamental carriers of information, because photons — the information carriers — are stationary in x_4.

2. Quantum nonlocality is three-dimensional shadow of four-dimensional coincidence on the null surface — already a holographic statement.

3. In curved spacetime, the natural generalization of the McGucken Sphere is the conformal boundary, where conformal symmetry (the symmetry of null surfaces) governs the boundary theory.

4. Encoding all bulk information on the conformal boundary as a CFT, with entanglement entropy given by extremal surface areas, is AdS/CFT — the precise mathematical realization of the holographic structure that the McGucken Principle generates.

The holographic principle's area scaling of information follows from the confinement of information carriers to null surfaces — and, more precisely, from the six-fold geometric identity of the expanding null surface (foliation, level sets, caustics, contact geometry, conformal geometry, and null-hypersurface cross-section), which constrains the boundary data to be a single, unified, correlated dataset rather than a collection of independent bits. This geometric nonlocality of the null surface is the physical mechanism that reduces degrees of freedom from volume to area. The Bekenstein-Hawking entropy follows from counting Planck-area cells on the horizon. The Ryu-Takayanagi formula admits a geometric interpretation in terms of null-surface channels through the minimal bulk surface. Jacobson's thermodynamic derivation of Einstein's equations, Verlinde's entropic gravity, and 't Hooft's original holographic bound are all consequences of the expanding fourth dimension.

Holographic duality is not an arbitrary discovery of string theory. It is a natural and structurally expected consequence of the McGucken Principle. Once one recognizes that information lives on null surfaces because the fourth dimension is expanding at c, the entire holographic program — from black hole entropy to AdS/CFT — follows as geometry.

And as the principle naturally exalts the light cone and expansive nature of the light sphere, the principle exalts the nonlocality of the light sphere (underlying quantum entanglement) where a photon has an equal chance of being measured anywhere on the sphere due to quantum mechanics. And so it is that in addition to the radiative arrow of time, we glimpse quantum mechanics alongside relativity — and now holography — in the McGucken Principle of the expanding fourth dimension.

The McGucken Principle is a foundational law from which the architecture of physical theory is reconstructed.

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