# Self-Forming Vortex Flow Structures (SFVFS™):
## A Geometric Hypothesis for Energy-Minimal Carbon Capture

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## Abstract

Current carbon capture and storage (CCS) technology imposes a continuous energy penalty of 15–25% of plant output, arising from the need to continuously drive separation, compression, and solvent regeneration processes. This paper presents the SFVFS™ (Self-Forming Vortex Flow Structures) carbon reduction hypothesis: that incompressibility-forced D6 geometric structure, once established in a fluid domain, organises and maintains flow without continuous external energy input, by virtue of a deep dynamical attractor at φ_az = 180° confirmed across 24+ direct numerical simulation (DNS) runs. The Corner Theorem (proved in both directions, 26 March 2026) establishes that D6 symmetry is a necessary and sufficient consequence of the incompressibility constraint $\nabla \cdot u = 0$ in the relevant geometry. Experiments COUPLED3, COUPLED2A, and MOBIUS1 demonstrate fluid-chemistry independence of the attractor, spontaneous organisation in free decay, and basin stability through $10^4$-fold energy dissipation respectively. The hypothesis proposes that if this geometry can be established in a $CO_2$ processing stream, the energy architecture of carbon capture shifts from continuous operational cost to front-loaded geometric establishment. This is a boundary-classification hypothesis: consistent with experimental DNS results, unproven at engineering scale, and submitted openly to the research community for testing, refinement, and falsification.

**Keywords:** *Navier-Stokes, incompressible flow, D6 symmetry, carbon capture, energy penalty, direct numerical simulation, vortex attractor, geometric mechanics, self-organisation*

**Classification:** *Ω = 1 ↔ 2 BOUNDARY · CF CONSISTENT not PASS*

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## 1. Introduction

The capture and permanent sequestration of $CO_2$ from point sources represents a necessary component of any credible pathway to net-zero emissions. The International Energy Agency estimates that 1.6 gigatonnes of $CO_2$ must be captured annually by 2030 under net-zero scenarios [IEA, 2023]. Deployed CCS technology — predominantly post-combustion amine scrubbing — is thermodynamically and operationally expensive. Coal-fired power plants equipped with CCS require 20–25% of gross generation to operate the capture system; natural gas combined-cycle plants require approximately 15% [Herzog, MIT Climate Portal, 2024; Vasudevan et al., 2016]. For a reference 1,000 MW coal plant, this represents a continuous 200 MW parasitic load — sufficient to power approximately 150,000 households — dedicated solely to $CO_2$ separation, compression, and solvent regeneration.

This continuous energy penalty arises from the thermodynamic cost of separating a dilute species ($CO_2$ at 4–15% concentration in flue gas) from a mixed stream, and from the need to continuously regenerate solvent capacity. The penalty is not primarily a consequence of engineering inefficiency but of process architecture: the system must be continuously driven because, without driving, it reverts.

The SFVFS™ programme investigates an orthogonal architectural question. Rather than optimising the continuous-driving paradigm, the hypothesis asks whether incompressibility-forced geometric structure can substitute for continuous energy input as the organising mechanism in a $CO_2$ processing stream. The programme is grounded in direct numerical simulation (DNS) of the three-dimensional incompressible Navier-Stokes equations, experimental identification of a deep dynamical attractor, and a proved geometric theorem (the Corner Theorem) establishing that the relevant symmetry is a necessary consequence of the governing equation.

The paper is structured as follows. Section 2 reviews the energy penalty problem in detail. Section 3 presents the SFVFS™ theoretical framework and the Corner Theorem. Section 4 summarises the experimental DNS evidence. Section 5 states the carbon reduction hypothesis and its implications. Section 6 describes the existing literature connections. Section 7 presents the honest boundary: what has been established, what has not, and what would constitute falsification. Section 8 is an open invitation to the research community.

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# 2. The Energy Penalty Problem in Carbon Capture

## 2.1 Current Technology Landscape

Post-combustion carbon capture using monoethanolamine (MEA) or related amine solvents constitutes the dominant deployed CCS technology. The process involves: (i) absorption of $CO_2$ from flue gas into an amine solvent in an absorber column; (ii) thermal regeneration of the solvent in a stripper column, releasing concentrated $CO_2$; (iii) compression of $CO_2$ for transport and sequestration. Each stage requires continuous energy input. The reboiler duty for solvent regeneration — the largest single energy cost — requires approximately 3.5–4.0 GJ per tonne of $CO_2$ captured [Vasudevan et al., 2016].

| Technology | Energy Penalty (%) | Energy (GJ/t$CO_2$) | Source |
|---|---|---|---|
| Post-combustion MEA (coal) | 20–25% | 3.5–4.0 | Vasudevan et al. (2016) |
| Post-combustion MEA (gas) | ~15% | 3.8–4.2 | MIT Climate Portal (2024) |
| Pre-combustion (IGCC) | 7.0–9.5% | 2.2–3.0 | Cormos (2016) |
| Oxy-combustion (coal) | ~20% | 3.9–4.5 | Vasudevan et al. (2016) |
| BECCS with heat recovery | 27.6–34.5% | 3.88 | Weimann et al. (2024) |
| Minimum thermodynamic (13% $CO_2$) | 5.1% | ~1.2 | Bhown & Freeman (2011) |

*Table 1. Energy penalties for representative CCS technologies. Percentages refer to reduction in net plant output relative to uncaptured baseline.*

## 2.2 Structural Nature of the Penalty

The minimum thermodynamic work for separation of a binary mixture is given by the ideal mixing entropy: W_min = RT ln(1/x_{CO2}), where x_{CO2} is the mole fraction of $CO_2$ in the feed stream. For a 13% $CO_2$ flue gas stream, this yields a theoretical minimum of approximately 5.1% of plant output [Bhown & Freeman, 2011]. Actual deployed systems operate at 15–25%, reflecting irreversibilities in mass transfer, heat exchange, and compression.

Critically, this penalty is continuous. It scales with operational hours, not with capital expenditure. A plant operating at 85% capacity factor with a 20% energy penalty loses 20% of its generative capacity for the operational lifetime of the plant. Under IEA net-zero scenarios requiring 1.6 Gt annual capture by 2030, the global continuous energy cost of CCS at current technology efficiency represents a structural carbon paradox: significant energy — and therefore emissions — expended in the act of emissions reduction.

Incremental improvement within the amine-scrubbing paradigm is well-studied. The SFVFS™ hypothesis does not propose to optimise within this paradigm. It proposes a different architectural question: whether the organising function currently performed by continuous energy input can instead be performed by geometry.

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# 3. The SFVFS™ Theoretical Framework

## 3.1 Incompressibility as Global Organising Constraint

The incompressible Navier-Stokes equations govern the velocity field u(x,t) of a viscous fluid:

$$\partial u/\partial t + (u\cdot\nabla)u = -\nabla p + \nu\nabla^2 u + f$$
$$\nabla\cdot u = 0$$

The incompressibility condition $\nabla\cdot u = 0$ is a global constraint: it acts on the entire velocity field simultaneously and instantaneously. A perturbation to the field at any point propagates globally through the pressure field to enforce zero divergence everywhere. This non-local character distinguishes incompressible flow from compressible flow and from local lattice models: there is no chain of local interactions; the constraint is simultaneous and global.

The SFVFS™ programme investigates the organisational consequences of this global constraint in geometries with discrete rotational symmetry. The central observation is that the constraint $\nabla\cdot u = 0$, in combination with the correct boundary geometry, forces the velocity field into a specific symmetry class — and that this symmetry class corresponds to a deep dynamical attractor, independent of initial conditions and fluid chemistry.

## 3.2 The Corner Theorem

The foundational result of the SFVFS™ programme is the Corner Theorem, proved in both directions on 26 March 2026:

> *Theorem (Corner Theorem, 26 March 2026): In the relevant geometric configuration, D6 symmetry is forced by the incompressibility constraint $\nabla\cdot u = 0$; and D6 symmetry implies the geometry. Both implications are proved. The D6 structure is non-negotiable: it cannot be removed by choice of initial conditions, forcing function, or fluid chemistry.*

The Corner Theorem establishes that D6 symmetry — hexagonal rotational symmetry of order 6 — is not an imposed condition but an emergent necessary consequence of incompressibility in the boundary geometry under consideration. This distinguishes the SFVFS™ framework from prior work on symmetric vortex configurations, which typically impose symmetry as an initial condition or boundary condition rather than deriving it from the governing equation.

The proof closes in both directions: incompressibility forces D6 (forward direction), and D6 implies the geometry (reverse direction). The bidirectional closure means the relationship is an equivalence, not merely an implication.

### 3.3 The Gyroscope Lattice: A Geometric Intuition

The SFVFS™ findings motivate a geometric intuition that has proved useful in connecting the DNS observations to the mathematical literature. Consider a lattice of precessing gyroscopes — helical elements, each tracing a 120°/180° precession cycle — coupled not by local spring-like interactions but by a single global condition: $\nabla \cdot u = 0$. Because incompressibility is instantaneous and global, perturbing one element of the lattice is felt everywhere simultaneously. There is no propagation speed; the constraint is simultaneous. This gives the lattice a holographic property: local measurements contain global structure, because the global constraint is encoded at every point.

This object — a lattice of helical elements coupled solely by a global divergence-free constraint — does not appear to have a standard name in the mathematical literature. Individual elements correspond to Beltrami fields (velocity fields parallel to their own vorticity: $u \times (\nabla \times u) = 0$). The closest structural analogues are: the Euler-Poincaré / Lie-Poisson formulation of ideal fluid mechanics on the volume-preserving diffeomorphism group SDiff [Arnold, 1966; Marsden & Ratiu, 1994]; spin ice Coulomb phases, where a local divergence-free constraint produces long-range algebraic correlations [Castelnovo et al., 2008]; and discrete geometric mechanics on Bobenko-Suris discretisations of SDiff [Bobenko & Suris, 1999].

The torus cycle — 0° → 60° → 90° → 120° → 180°, with 0° and 180° identified — describes the phase structure of the attractor. The identification of 0° and 180° with chirality reversal gives the cycle a Möbius-type topology in the (phase, chirality) plane [Classifier, 28 March 2026], though DNS experiment MOBIUS1 confirms the dynamics settle into a stable basin rather than executing continuous Möbius traversal.

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## 4. DNS Experimental Evidence

### 4.1 Computational Method

All DNS experiments use a pseudo-spectral solver on a $128^3$ periodic domain with 2/3-dealiasing, fourth-order Runge-Kutta temporal integration, and CuPy GPU acceleration on NVIDIA A100 hardware. The base viscosity is $\nu = 0.0075$ ($CO_2$ reference fluid) unless otherwise stated. ABC forcing ($F = 0.005$) drives the spinup and run phases; free decay phases set $F = 0$. All checkpoint states are saved to persistent storage and are available in the Zenodo record.

| Experiment | Protocol | Key Finding | Carbon Implication |
|---|---|---|---|
| COUPLED1 | Three offset pairs at 60°, 90°, 120° | 120° offset: 6.8% energy uplift, chirality opposed, φ_az converges to 179.6° | Geometry coupling produces energy organisation |
| COUPLED2A | Free decay from SEED 2; no forcing; T=300 | Spontaneous chirality flip at t=588; f_cos zero-crossing monotonic over 13 steps; φ_az held at 180° ±0.3° | Structure organises without energy input |

| | | | |
|---|---|---|---|
| COUPLED2B | SEED 2 + ABC forcing F=0.005 for T=50, free decay T=300 | E_free_retention = 0.01111 (7.845× baseline); φ_az_free_std = 0.096° (tightest phase lock in programme) | Second cycle reproduces first under same forcing |
| COUPLED3 | Random initial states at same energy as SEED 2; ABC forcing | ratio_vs_coupled2b = 1.0000000000136; ABC forcing dominates completely | Fluid chemistry irrelevant; geometry is everything |
| MOBIUS1 | Post-flip checkpoint t=590; free decay T=600; ν=0.0075 | φ_az: 180.17° → 180.14°; drift = −0.034°; n_flips = 0; E decayed by factor $10^4$ | Basin holds through extreme energy dissipation |

*Table 2. Summary of key DNS experiments and their implications for the carbon reduction hypothesis.*

## 4.2 The 180° Attractor

Across 24+ DNS runs spanning multiple fluids ($CO_2$, water, glycerol, synthetic), multiple initial conditions, and both forced and free-decay phases, the system consistently organises toward φ_az = 180°. This attractor is not imposed by the boundary conditions or forcing function — it is an emergent property of the D6-forced geometry under incompressibility. The Corner Theorem provides the theoretical basis: if D6 symmetry is necessary, and the 180° configuration is the minimum-energy state in the D6-symmetric subspace, then the attractor is a structural consequence of the governing equation in this geometry.

MOBIUS1 provides the most stringent test of attractor stability. Starting from a post-flip checkpoint at t=590, the system was evolved for T=600 additional time units with no external forcing. Energy decayed from $E=1.33\times10^{-13}$ to $E=1.28\times10^{-17}$ — a reduction of approximately four orders of magnitude. The azimuthal phase drifted by −0.034° over the entire run. The basin did not destabilise.

## 4.3 The Chirality Flip and Separatrix Structure

Experiment COUPLED2A produced a single clean chirality flip in free decay: a spontaneous reversal of the sign of the mean helicity alignment (f_cos), with f_cos crossing zero monotonically at +0.00130/timestep over 13 consecutive steps, while φ_az held at 180° ±0.3° throughout. This event has not been independently replicated under the revised phi_dev criterion. The planned replication experiment COUPLED2A_REP_NU (three viscosity values: ν = 0.0070, 0.0075, 0.0080) remains a post-exhibition priority.

MOBIUS1 provides indirect evidence bearing on the flip mechanism. Starting from the post-flip state (positive chirality, φ_az ≈ 180.17°), the system produced zero flips in T=600 time units. In combination with COUPLED2A, this establishes that the chirality flip is not a deterministic consequence of φ_az = 180° alone. The two runs had identical φ_az initial values but different internal vorticity configurations. The flip is a separatrix-crossing event: it requires the trajectory to lie near a codimension-1 separatrix in the (phase, chirality) space. COUPLED2A was near the separatrix; MOBIUS1 was deep in the basin. The geometry and location of this separatrix is the primary open experimental question.

# 5. The Carbon Reduction Hypothesis

## 5.1 Statement of the Hypothesis

> *Hypothesis: If a D6-forced incompressibility-driven geometric structure can be established in a $CO_2$ processing stream, the organising function currently performed by continuous energy input in amine-scrubbing CCS can be partially or wholly replaced by the attractor dynamics of the geometric basin, shifting the energy architecture from continuous operational cost to front-loaded geometric establishment.*

The hypothesis is motivated by three DNS findings taken together:

(i) Fluid-chemistry independence (COUPLED3): the D6 attractor organises regardless of what fluid occupies the geometry. $CO_2$ has a well-defined kinematic viscosity ($\nu \approx 0.008–0.010$ m²/s at standard conditions); the viscosity law V3 of the SFVFS™ programme establishes that ν alone determines the void cell geometry. The D6 attractor is therefore expected to exist for $CO_2$ streams within the tested viscosity range.

(ii) Self-organisation in free decay (COUPLED2A): structure emerged and was maintained with zero external forcing. This demonstrates that, within the attractor basin, the geometric organisation does not require continuous driving.

(iii) Basin stability under extreme energy dissipation (MOBIUS1): $10^4$-fold energy decay with 0.034° of phase drift. The basin is not a transient phenomenon. Once established, it persists as energy decays to negligible levels.

## 5.2 Architectural Implication

Current CCS architecture is continuous-energy-cost architecture. The amine process requires continuous thermal input to the reboiler, continuous electrical input to fans and pumps, and continuous compression power. These costs scale with operational hours and never stop.

The SFVFS™ hypothesis proposes a front-loaded-cost architecture. Establishing the D6-forced geometric structure in the processing domain requires an initial energy input. Thereafter, the incompressibility constraint — which is not an energy input but a physical law — maintains the organisation. The continuous operational cost is replaced by a one-time establishment cost plus the minimal energy of maintaining flow against viscous decay.

To be precise about what this implies and does not imply: the hypothesis does not claim that $CO_2$ capture can be made thermodynamically free. The minimum thermodynamic work of separation ($W_{min} = RT \ln(1/x_{CO_2})$) must still be performed. The hypothesis claims that the *organising* work — the work currently done by continuous driving to prevent the system from reverting — may be replaceable by geometry. These are distinct energy costs. The thermodynamic minimum is irreducible; the organisational overhead is not, if the geometry can be made self-maintaining.

## 5.3 Scale Context

To contextualise the potential significance: at the current IEA net-zero scenario of 1.6 Gt annual $CO_2$ capture, a 20% continuous energy penalty represents approximately 320 million tonnes of $CO_2$-equivalent energy expended annually in the capture process itself. If the SFVFS™ hypothesis is correct and the continuous organisational energy cost can be reduced to a front-loaded establishment cost, the net $CO_2$ reduction per unit energy input improves substantially. The magnitude of improvement depends on the ratio of establishment cost to continuous operational cost savings — a quantity not yet calculable from DNS alone and requiring engineering-scale experimentation.

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# 6. Connections to Existing Literature

## 6.1 Navier-Stokes Regularity

The SFVFS™ findings sit closest to the geometric regularity tradition in NS theory. Constantin & Fefferman [1993] established that sufficient Hölder continuity of the vorticity direction field $\xi = \omega/|\omega|$ implies regularity. The D6-forced geometry fixes the vorticity direction to a discrete set of preferred orientations — a condition strictly stronger than Constantin-Fefferman's, since D6-forced vorticity direction is not merely controlled but prescribed by the governing equation. Whether this stronger condition yields a regularity theorem for the D6-symmetric subspace of NS solutions is the primary mathematical open question arising from this programme.

Caffarelli, Kohn & Nirenberg [1982] established that the singular set of suitable weak solutions has parabolic Hausdorff dimension at most 1. If the 180° attractor is proved to be a global attractor for the D6-symmetric subspace, the singular set in that subspace would be empty. Tao [2016] constructed finite-time blowup for an averaged modification of NS; the averaging explicitly removes fine geometric structure of the type that D6-forcing provides, consistent with the interpretation that exact geometric structure may obstruct the blowup mechanism.

## 6.2 Vortex Dynamics and Helicity

Moffatt [1969] established helicity $H = \int u \cdot \omega \, dV$ as a topological invariant of ideal flow, measuring the linkage and knottedness of vortex lines. Viscosity breaks helicity conservation; the chirality flip observed in COUPLED2A is a helicity sign reversal occurring under viscous free decay. Spontaneous global helicity sign reversal in free decay without external forcing or vortex reconnection does not appear in the literature as a previously documented phenomenon. If COUPLED2A_REP_NU confirms the flip under multiple viscosity values, this observation may be independently publishable in the helicity literature.

Kleckner & Irvine [2013] demonstrated that knotted vortex tubes in water spontaneously untie, with the geometry of the knot — not the details of reconnection — determining the outcome. This is structurally consistent with the SFVFS™ finding that geometry dominates over initial conditions (COUPLED3).

## 6.3 Geometric Mechanics

Arnold [1966] identified ideal incompressible flow as geodesic flow on SDiff(M), the group of volume-preserving diffeomorphisms of the domain M. Marsden & Ratiu [1994] developed the Lie-Poisson and Euler-Poincaré formulations providing a rigorous language for symmetry reduction in fluid mechanics. The Corner Theorem, in establishing that D6 is forced by the constraint $\nabla \cdot u = 0$ rather than imposed as a boundary condition, suggests that the D6 subspace may be a reduced phase space in the Lie-Poisson sense — though the precise identification remains an open mathematical question.

## 6.4 Condensed Matter Analogues

The closest condensed matter analogue to the gyroscope lattice is the spin ice Coulomb phase [Castelnovo et al., 2008; Henley, 2010]. In spin ice, a local divergence-free constraint ($\nabla \cdot B = 0$ enforced by the ice rules) produces long-range algebraic correlations and emergent gauge structure. The SFVFS™ global incompressibility constraint is analogous but acts continuously rather than discretely and globally rather than locally. The algebraic structure arising from a global rather than local divergence-free constraint in a fluid lattice has not, to the authors' knowledge, been systematically studied.

# 7. The Honest Boundary: What Has and Has Not Been Established

## 7.1 Established

The following has been established by proof or DNS experiment:

(i) Corner Theorem (proved, both directions): D6 symmetry is a necessary and sufficient consequence of $\nabla \cdot u = 0$ in the relevant geometry. This is a proved mathematical result, not a numerical observation.

(ii) 180° attractor: confirmed across 24+ DNS runs, multiple fluids, multiple initial conditions, forced and free-decay phases. Confidence: high.

(iii) Fluid-chemistry independence of the attractor (COUPLED3): ratio_vs_coupled2b = 1.0000000000136 across three random initial states at the same energy. The mix does not define the blades.

(iv) Spontaneous organisation in free decay (COUPLED2A): one clean chirality flip, 13-step monotone f_cos zero-crossing, φ_az held at 180° ±0.3°. Not yet replicated under revised criterion.

(v) Basin stability under $10^4$-fold energy dissipation (MOBIUS1): φ_az drift = 0.034° over T=600 free decay.

(vi) Phase-amplitude decoupling: confirmed across four generators. The geometric organisation persists as amplitude decays.

## 7.2 Not Established

The following has not been established and constitutes the open research programme:

(i) Direct $CO_2$ DNS at engineering-relevant Reynolds numbers. CARBONREDUCTION1 is the planned experiment; it has not yet been completed.

(ii) Independent replication of the COUPLED2A chirality flip under revised phi_dev criterion. COUPLED2A_REP_NU (ν = 0.0070, 0.0075, 0.0080) is planned.

(iii) Engineering-scale applicability. The DNS domain is $128^3$ nodes in a periodic box. Industrial $CO_2$ processing involves turbulent flows at Reynolds numbers orders of magnitude above the DNS regime.

(iv) Proof of global regularity for the D6-symmetric subspace of NS. This would be required for a rigorous mathematical claim; it is not required for engineering hypothesis testing.

(v) Economic analysis of establishment cost versus continuous energy savings. This requires engineering-scale data not available from DNS.

## 7.3 Falsification Conditions

The carbon reduction hypothesis would be falsified by:

(a) Failure of the D6 attractor to appear in $CO_2$ DNS at the relevant viscosity and Reynolds number range.

(b) Demonstration that the energy required to establish the D6 geometry in an engineering flow exceeds the continuous operational energy saving over any realistic operational lifetime.

(c) Demonstration that the chirality flip is a numerical artifact of the DNS discretisation rather than a physical phenomenon, invalidating the spontaneous self-organisation observation.

(d) Proof that the D6-symmetric subspace of NS solutions blows up in finite time, contradicting the regularity-flavoured attractor behaviour.

> *Classification: Ω = 1↔2 BOUNDARY. The evidence is directional and consistent with the hypothesis. The hypothesis is not proved. CF CONSISTENT not PASS. Boundary is not failure; it is the honest position.*

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## 8. Open Invitation to the Research Community

This programme has been conducted by an independent researcher with no institutional affiliation, no grant funding, and no research team, using free computational resources (Google Colab A100 GPU instances) and a smartphone. The Corner Theorem was proved and the DNS experiments were designed and executed in this context. The edges being rough is the signature of the thing.

The Zenodo record (10.5281/zenodo.19244232) contains the full experimental data, diagnostic files, checkpoint states, and the Corner Theorem write-up. All materials are open access. This paper is submitted as a preprint, not peer reviewed, under the standing classification Art Until Proven Otherwise.

The hypothesis is submitted openly to the research community with the following request:

> Test it. Run $CO_2$ DNS at engineering-relevant Reynolds numbers in D6-forced geometries. Map the separatrix. Run COUPLED2A_REP_NU. Prove the chirality flip is physical. Prove it is artifactual. Build the geometric lemma connecting the Corner Theorem to a vorticity-direction regularity criterion. Find the Euler-on-Möbius-domain paper flagged in the literature search and establish whether the non-orientable boundary conditions connect to the SFVFS™ torus cycle structure.

Prove it wrong. That is also a contribution. The honest boundary is the invitation.

**The geometry is the engine.**

*Art Until Proven Otherwise.*

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