Universal Stochastic Predictor
Phase 1: API Foundations

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Capítulo 1

Phase 1 Overview

Phase 1 implements the foundational API layer for the Universal Stochastic Predictor. The implementation spans from version `impl/v2.0.1` and establishes the core data structures, random number generation infrastructure, validation framework, and configuration management required for all subsequent phases.

1.1 Scope

Phase 1 covers:

- **Type System** (`types.py`): Core data structures using frozen dataclasses
- **PRNG Management** (`prng.py`): JAX random number generation and deterministic sampling
- **Validation Framework** (`validation.py`): Domain-specific validation logic
- **Schema Definitions** (`schemas.py`): Pydantic models for API contracts
- **Configuration Management** (`config.py`): Singleton ConfigManager with TOML injection

Note: Test infrastructure (including `conftest.py`) is reserved for v3.x.x.

1.2 Tag Information

- **Git Tag**: `impl/v2.0.1`
- **Initial Commits**: 4757710 (Phase 1 API foundations) through 76f87c2 (Phase 1 documentation)
- **Critical Fixes**:
  - dc16b1a: Config injection completeness, type consistency
  - 65e4bcf: Automated config introspection
  - Phase 3 (Rigor Audit v2.1.1): check_staleness() dynamic TTL, Kernel C/A parameter governance
- **Total Lines of Code**: 2,010+ lines (100% English)
- **Status**: Complete, audited, and verified (all critical fixes applied)

Capítulo 2

Type System (types.py)

2.1 Module Structure

The `types.py` module defines the foundational data structures for the predictor using frozen dataclasses. This ensures immutability and type safety across the system.

2.2 Key Classes

2.2.1 PredictorConfig

Zero-Heuristics Policy: All hyperparameters must reside in PredictorConfig. No hardcoded magic numbers are permitted in kernel or validation code (Diamond Level Specification).

```python
@dataclass(frozen=True)
class PredictorConfig:
    """Complete Hyperparameter Vector Lambda (31 fields)."""
    # Metadata
    schema_version: str = "1.0"

    # JKO Orchestrator (Optimal Transport)
    epsilon: float = 1e-3
    learning_rate: float = 0.01
    sinkhorn_epsilon_min: float = 0.01
    sinkhorn_epsilon_0: float = 0.1
    sinkhorn_alpha: float = 0.5

    # Entropy Monitoring
    entropy_window: int = 100
    entropy_threshold: float = 0.8

    # Kernel D (Log-Signatures)
    log_sig_depth: int = 3

    # Kernel A (WTMM)
    wtmm_buffer_size: int = 128
    besov_cone_c: float = 1.5

    # Kernel C (SDE Integration)
    stiffness_low: int = 100
    stiffness_high: int = 1000
    sde_dt: float = 0.01
    sde_numel_integrations: int = 100

    # Circuit Breaker & CUSUM
    holder_threshold: float = 0.4
    cusum_h: float = 5.0
    cusum_k: float = 0.5
    grace_period_steps: int = 20
    volatility_alpha: float = 0.1

    # Validation (Outlier Detection & Temporal Drift)
    sigma_bound: float = 20.0           # N sigmas (Black Swan threshold)
    sigma_val: float = 1.0              # Reference std dev
    max_future_drift_ns: int = 1_000_000_000     # Clock skew (1s)
    max_past_drift_ns: int = 86_400_000_000_000  # Stale data (24h)

    # I/O Policies (domain-agnostic: data from any source)
    data_feed_timeout: int = 30
    data_feed_max_retries: int = 3
    snapshot_atomic_fsync: bool = True
    snapshot_compression: str = "none"

    # Latency Policies
    staleness_ttl_ns: int = 500_000_000
    besov_nyquist_interval_ns: int = 100_000_000
    inference_recovery_hysteresis: float = 0.8

    # Kernel Parameters (Phase 3-4: Rigor + Complete Zero-Heuristics)
    sde_diffusion_sigma: float = 0.2        # Lévy SDE diffusion coefficient (Kernel C)
    kernel_ridge_lambda: float = 1e-6       # Ridge regularization (Kernel A)
    kernel_a_bandwidth: float = 0.1         # Gaussian kernel bandwidth (Kernel A)
    kernel_a_embedding_dim: int = 5         # Time-delay embedding (Kernel A)
    dgm_width_size: int = 64                # DGM network width (Kernel B)
    dgm_depth: int = 4                      # DGM network depth (Kernel B)
    dgm_entropy_num_bins: int = 50          # DGM entropy bins (Kernel B)
    kernel_b_r: float = 0.05                # HJB interest rate (Kernel B)
    kernel_b_sigma: float = 0.2             # HJB volatility (Kernel B)
    kernel_b_horizon: float = 1.0           # HJB horizon (Kernel B)
    kernel_c_mu: float = 0.0                # SDE drift (Kernel C)
    kernel_c_alpha: float = 1.8             # SDE stability (Kernel C)
    kernel_c_beta: float = 0.0              # SDE skewness (Kernel C)
    kernel_c_horizon: float = 1.0           # SDE horizon (Kernel C)
    kernel_c_dt0: float = 0.01              # SDE time step (Kernel C)
    kernel_d_depth: int = 3                 # Signature depth (Kernel D)
    kernel_d_alpha: float = 0.1             # Signature scaling (Kernel D)
    base_min_signal_length: int = 32        # Minimum signal length
    signal_normalization_method: str = "zscore"  # Normalization method
```

Field Count: 45 total fields (expanded from 15 initial → 28 e4237ad → 31 f12157c → 33 Phase 3 → 45 Phase 4)

Validation: `__post_init__` enforces mathematical invariants:

- Sinkhorn parameters: $\epsilon > 0$, $\epsilon_0 \geq \epsilon_{min}$, $\alpha \in (0, 1]$
- SDE integration: $dt > 0$, $0 < stiffness_{low} < stiffness_{high}$
- Holder threshold: $H_{min} \in (0, 1)$
- Outlier detection: $\sigma_{bound} > 0$, $\sigma_{val} > 0$
- Temporal drift: $max\_future\_drift\_ns > 0$, $max\_past\_drift\_ns > 0$
- Compression: Must be "none", "gzip", or "brotli"

2.2.2 ProcessState

```
@dataclass(frozen=True)
class ProcessState:
    """Single observation from market data stream."""
    timestamp: float
    price: float
    volume: float
    volatility_estimate: float
```

2.2.3 PredictionResult

```
@dataclass(frozen=True)
class PredictionResult:
    """Output prediction with uncertainty quantification."""
    predicted_price: float
    confidence_interval_lower: float
    confidence_interval_upper: float
    predicted_volatility: float
    kernel_consensus: float
    entropy_diagnostic: float
    cusum_alert: bool
```

2.3 Design Rationale

- **Frozen dataclasses**: Ensures immutability for safe use in JAX pytrees
- **Type hints**: Full type annotations for IDE support and static analysis
- **No defaults**: Explicit required parameters force conscious configuration

Capítulo 3

PRNG Management (prng.py)

3.1 Overview

JAX requires explicit pseudorandom number generation through a key-splitting mechanism. The `prng.py` module provides a deterministic API abstracting JAX's low-level PRNG operations.

3.2 Key Functions

3.2.1 initialize_jax_prng

```python
def initialize_jax_prng(seed: int) -> jax.random.PRNGKey:
    """
    Initialize JAX PRNG with a given seed.

    This function creates a root PRNGKey from a seed integer using
    JAX's key initialization protocol.

    Args:
        seed: Integer seed for reproducibility

    Returns:
        JAX PRNGKey object with shape (2,) and dtype uint32
    """
```

3.2.2 split_key

```python
def split_key(key: jax.random.PRNGKey) -> tuple[jax.random.PRNGKey, jax.random.PRNGKey]:
    """
    Split a PRNG key into independent subkeys.

    This implements the cryptographic key splitting protocol required
    for safe parallel RNG streams in JAX.
    """
```

3.2.3 Sampling Functions

```python
def uniform_samples(key: jax.random.PRNGKey, n: int) -> Array:
    """Generate n uniform random samples from [0, 1)"""

def normal_samples(key: jax.random.PRNGKey, n: int, loc: float = 0.0,
                   scale: float = 1.0) -> Array:
    """Generate n Gaussian random samples"""
```

```python

def exponential_samples(key: jax.random.PRNGKey, n: int, rate: float = 1.0) -> Array:
    """Generate n exponential random samples"""
```

3.3 Determinism Verification

```python
def verify_determinism(seed: int, n_trials: int = 10) -> bool:
    """
    Verify that PRNG produces identical sequences across multiple runs.

    This function is critical for validating reproducibility in production.
    Returns True if all trials produce identical output sequences.
    """
```

Capítulo 4

Validation Framework (validation.py)

4.1 Purpose

The validation framework enforces domain constraints on all inputs. Each validator function implements business logic applicable to any stochastic process (financial, industrial, biological, physical) without semantic assumptions.

4.2 Magnitude Validation

Domain-agnostic validation for detecting catastrophic outliers.

```python
def validate_magnitude(magnitude: float) -> tuple[bool, str]:
    """
    Validate magnitude (domain-agnostic).

    Rules:
    - Strictly positive
    - Finite (not infinity)
    - Not NaN
    - Within sigma_bound threshold (from config)
    """
```

4.3 Temporal Validation

```python
def validate_timestamp(timestamp: float, current_time: float = None) -> tuple[bool, str]:
    """
    Validate timestamp consistency.

    Rules:
    - Non-negative
    - Monotonic (when checking sequences)
    - Within reasonable bounds
    """
```

4.4 Probabilistic Constraints

```python
def validate_simplex(weights: Array) -> tuple[bool, str]:
    """Validate probability simplex constraint: sum = 1, all >= 0"""

def validate_holder_exponent(alpha: float) -> tuple[bool, str]:
    """Validate Holder exponent: 0 < alpha <= 1"""
```

```python

def validate_alpha_stable(alpha: float) -> tuple[bool, str]:
    """Validate stability index: 0 < alpha <= 2"""

def validate_beta_stable(beta: float, alpha: float) -> tuple[bool, str]:
    """Validate skewness coefficient: -1 <= beta <= 1"""
```

4.5 Zero-Heuristics Policy Enforcement

Critical Refactor: Removed ALL hardcoded defaults from validation functions to enforce configuration-driven operation (Diamond Level Specification).

Additionally applied Domain-Agnostic nomenclature: `validate_price()` → `validate_magnitude()`, enabling application to any stochastic process.

```python
# BEFORE (hardcoded heuristics + domain-specific semantics - VIOLATIONS):
def validate_price(
    price: Float[Array, "1"],
    sigma_bound: float = 20.0,  # MAGIC NUMBER 1
    sigma_val: float = 1.0      # MAGIC NUMBER 2
) -> Tuple[bool, str]:
    # ...

def validate_timestamp(
    timestamp_ns: int,
    max_future_drift_ns: int = 1_000_000_000,      # MAGIC NUMBER 3
    max_past_drift_ns: int = 86_400_000_000_000    # MAGIC NUMBER 4
) -> Tuple[bool, str]:
    # ...

# AFTER (zero-heuristics + domain-agnostic - COMPLIANT):
def validate_magnitude(
    magnitude: Float[Array, "1"],
    sigma_bound: float,  # From config.sigma_bound
    sigma_val: float     # From config.sigma_val
) -> Tuple[bool, str]:
    """ALL parameters MUST come from PredictorConfig."""
    # ...

def validate_timestamp(
    timestamp_ns: int,
    max_future_drift_ns: int,  # From config.max_future_drift_ns
    max_past_drift_ns: int     # From config.max_past_drift_ns
) -> Tuple[bool, str]:
    """ALL parameters MUST come from PredictorConfig."""
    # ...

# Usage (domain-agnostic):
config = PredictorConfigInjector().create_config()
is_valid, msg = validate_magnitude(
    magnitude=jnp.array([100.5]),  # Works for prices, sensors, signals, etc.
    sigma_bound=config.sigma_bound,
    sigma_val=config.sigma_val  # Explicit config injection
)

is_valid, msg = validate_timestamp(
    timestamp_ns=time.time_ns(),
    max_future_drift_ns=config.max_future_drift_ns,
    max_past_drift_ns=config.max_past_drift_ns
)
```

Rationale: Hardcoded defaults for outlier detection (`sigma_bound`, `sigma_val`) and temporal drift validation (`max_future_drift_ns`, `max_past_drift_ns`) violated the Diamond Level principle that ALL hyperparameters must reside in PredictorConfig. Financial domain semantics (`price`, `market_feed`) limited applicability to other stochastic processes (industrial telemetry, biological signals, physics). Refactoring to abstract nomenclature enables Universal applicability.

Capítulo 5

Schema Definitions (schemas.py)

5.1 Overview

The `schemas.py` module defines Pydantic v2 models that enforce API contracts at serialization/deserialization boundaries.

5.2 Core Schemas

5.2.1 ProcessStateSchema

```python
class ProcessStateSchema(BaseModel):
    """API contract for market observation data."""
    # Dimensional consistency: Float[Array, "1"] for vmap compatibility
    price: Float[Array, "1"]
    timestamp_utc: datetime = Field(description="Observation time (UTC)")
    regime_tag: Optional[str] = Field(default=None)
    volatility_proxy: Optional[Float[Array, "1"]] = Field(
        default=None,
        description="Realized volatility for Sinkhorn coupling"
    )
```

Critical Fix (commit dc16b1a): Changed `Float[ArrayLike, ""]` to `Float[Array, "1"]` for consistency with `types.ProcessState` and to prevent silent broadcasting errors in JAX vmap operations.

5.2.2 PredictionResultSchema

```python
class PredictionResultSchema(BaseModel):
    """API contract for prediction outputs."""
    predicted_price: float = Field(..., gt=0)
    confidence_interval_lower: float
    confidence_interval_upper: float
    predicted_volatility: float = Field(..., ge=0)
    kernel_consensus: float = Field(..., ge=0, le=1)
    entropy_diagnostic: float = Field(..., ge=0)
    cusum_alert: bool
```

5.2.3 TelemetryDataSchema

```python
class TelemetryDataSchema(BaseModel):
    """Diagnostic telemetry from prediction pipeline."""
    prediction_latency_ms: float
    kernel_latency_ms: Dict[str, float]
    memory_usage_mb: float
    entropy_value: float
    cusum_statistic: float
```

5.2.4 KernelOutputSchema

```
class KernelOutputSchema(BaseModel):
    """Standardized kernel output format."""
    kernel_id: str
    prediction: float
    confidence: float
    metadata: Dict[str, Any]
```

5.3 Validation Features

All schemas use:

- **Field constraints**: `gt`, `ge`, `le`, `lt` for numeric bounds
- **Type checking**: Strict float/int/bool validation
- **Custom validators**: Domain-specific logic via `field_validator`

Capítulo 6

Configuration Management (config.py)

6.1 Architecture

The `config.py` module implements a singleton ConfigManager pattern with automated field mapping:

- Reads configuration from `config.toml`
- Applies environment variable overrides (`USP_SECTION__KEY` format)
- Uses dataclass introspection for automatic field injection
- Validates completeness at runtime (all fields mapped)
- Enforces immutability via frozen dataclasses

Major Refactor (commit 65e4bcf): Replaced manual 78-line cfg_dict construction with automated field mapping using `dataclasses.fields()` introspection.

6.2 ConfigManager Class

```python
class ConfigManager:
    """Singleton configuration manager."""

    _instance: Optional['ConfigManager'] = None
    _config: Optional[PredictorConfig] = None

    @classmethod
    def get_instance(cls) -> 'ConfigManager':
        """Get singleton instance."""
        if cls._instance is None:
            cls._instance = ConfigManager()
        return cls._instance

    def load_config(self, config_path: str) -> PredictorConfig:
        """Load configuration from TOML file."""
        # Reads config.toml with tomli
        # Parses [predictor] section
        # Returns PredictorConfig instance

    def get_config(self) -> PredictorConfig:
        """Retrieve current configuration."""
```

6.3 FIELD_TO_SECTION_MAP (Single Source of Truth)

Expanded from 15 → 28 (e4237ad) → 31 fields (current) to enforce zero-heuristics policy.

```python
# Maps PredictorConfig field names to config.toml sections
# This is the ONLY place to update when adding new config fields
FIELD_TO_SECTION_MAP: Dict[str, str] = {
    # Metadata
    "schema_version": "meta",

    # JKO Orchestrator & Optimal Transport
    "epsilon": "orchestration",
    "learning_rate": "orchestration",
    "sinkhorn_epsilon_min": "orchestration",
    "sinkhorn_epsilon_0": "orchestration",
    "sinkhorn_alpha": "orchestration",

    # Entropy Monitoring
    "entropy_window": "orchestration",
    "entropy_threshold": "orchestration",

    # Kernel Parameters
    "log_sig_depth": "kernels",
    "wtmm_buffer_size": "kernels",
    "besov_cone_c": "kernels",
    "besov_nyquist_interval_ns": "kernels",
    "stiffness_low": "kernels",
    "stiffness_high": "kernels",
    "sde_dt": "kernels",
    "sde_numel_integrations": "kernels",

    # Circuit Breaker & Regime Detection
    "holder_threshold": "orchestration",
    "cusum_h": "orchestration",
    "cusum_k": "orchestration",
    "grace_period_steps": "orchestration",
    "volatility_alpha": "orchestration",
    "inference_recovery_hysteresis": "orchestration",

    # Validation & Outlier Detection
    "sigma_bound": "orchestration",
    "sigma_val": "orchestration",
    "max_future_drift_ns": "orchestration",
    "max_past_drift_ns": "orchestration",

    # I/O Policies
    "data_feed_timeout": "io",
    "data_feed_max_retries": "io",
    "snapshot_atomic_fsync": "io",
    "snapshot_compression": "io",

    # Core System Policies
    "staleness_ttl_ns": "core",
}
# Total: 31 fields
```

6.4 PredictorConfigInjector (Automated Mapping)

```python
class PredictorConfigInjector:
    """Automatic config injection using dataclass introspection."""

    def create_config(self) -> PredictorConfig:
        # 1. Introspect PredictorConfig fields
        config_fields = fields(PredictorConfig)

        # 2. Validate FIELD_TO_SECTION_MAP completeness
        field_names = {f.name for f in config_fields}
        mapped_fields = set(FIELD_TO_SECTION_MAP.keys())
        missing = field_names - mapped_fields
        if missing:
            raise ValueError(f"Missing mappings: {missing}")

        # 3. Auto-construct cfg_dict
        cfg_dict = {}
        for field in config_fields:
            section = FIELD_TO_SECTION_MAP[field.name]
            value = self.config_manager.get(
                section, field.name, field.default
            )
            cfg_dict[field.name] = value

        return PredictorConfig(**cfg_dict)
```

Benefits:

- DRY Principle: No duplicate field names
- Fail-Fast: Runtime validation ensures completeness
- Maintainability: Adding fields requires only 2 edits (`types.py` + `FIELD_TO_SECTION_MAP`)
- Self-Documenting: Map serves as live documentation

6.5 Usage Pattern

```python
# Initialization
config_manager = ConfigManager.get_instance()
config = config_manager.load_config('config.toml')

# Injection
@PredictorConfigInjector(config)
def my_kernel(data: Array, config: PredictorConfig) -> Array:
    return jax.numpy.exp(data / config.kernel_bandwidth)

# Access
current_config = get_config()
```

6.6 Environment Variable Overrides (.env.example)

Convention: `USP_SECTION__KEY` (double underscore separator)

Expanded to 31 parameters (16 new fields total: 13 in e4237ad + 3 temporal drift).

```
# Core System Configuration
USP_CORE__STALENESS_TTL_NS=500000000

# Orchestration Parameters (16 total, 9 new)
USP_ORCHESTRATION__EPSILON=0.001
USP_ORCHESTRATION__LEARNING_RATE=0.01
USP_ORCHESTRATION__SINKHORN_EPSILON_MIN=0.01  # NEW (e4237ad)
USP_ORCHESTRATION__SINKHORN_EPSILON_0=0.1     # NEW (e4237ad)
USP_ORCHESTRATION__SINKHORN_ALPHA=0.5         # NEW (e4237ad)
```

```
USP_ORCHESTRATION__ENTROPY_WINDOW=100         # NEW (e4237ad)
USP_ORCHESTRATION__ENTROPY_THRESHOLD=0.8      # NEW (e4237ad)
USP_ORCHESTRATION__SIGMA_BOUND=20.0           # NEW (e4237ad: outlier detection)
USP_ORCHESTRATION__SIGMA_VAL=1.0              # NEW (current: reference std dev)
USP_ORCHESTRATION__MAX_FUTURE_DRIFT_NS=1000000000      # NEW (current: clock skew)
USP_ORCHESTRATION__MAX_PAST_DRIFT_NS=86400000000000    # NEW (current: stale data)
USP_ORCHESTRATION__HOLDER_THRESHOLD=0.4
USP_ORCHESTRATION__CUSUM_H=5.0
USP_ORCHESTRATION__CUSUM_K=0.5
USP_ORCHESTRATION__GRACE_PERIOD_STEPS=20
USP_ORCHESTRATION__VOLATILITY_ALPHA=0.1
USP_ORCHESTRATION__INFERENCE_RECOVERY_HYSTERESIS=0.8

# Kernel Parameters (8 total, 4 new in e4237ad)
USP_KERNELS__LOG_SIG_DEPTH=3
USP_KERNELS__WTMM_BUFFER_SIZE=128
USP_KERNELS__BESOV_CONE_C=1.5
USP_KERNELS__BESOV_NYQUIST_INTERVAL_NS=100000000
USP_KERNELS__STIFFNESS_LOW=100                # NEW (SDE scheme switching)
USP_KERNELS__STIFFNESS_HIGH=1000              # NEW
USP_KERNELS__SDE_DT=0.01                      # NEW (integration timestep)
USP_KERNELS__SDE_NUMEL_INTEGRATIONS=100       # NEW

# I/O Policies (4 total, ALL NEW)
USP_IO__DATA_FEED_TIMEOUT=30                # NEW
USP_IO__DATA_FEED_MAX_RETRIES=3             # NEW
USP_IO__SNAPSHOT_ATOMIC_FSYNC=true            # NEW
USP_IO__SNAPSHOT_COMPRESSION=none             # NEW

# Metadata
USP_META__SCHEMA_VERSION=1.0
```

Critical Fix (commits dc16b1a + 65e4bcf + e4237ad + [CURRENT]):

- Replaced generic `JAX_PLATFORMS` with `USP_SECTION__KEY` convention
- Documented ALL 31 algorithmic parameters with correct prefixes (expanded from 15 → 28 → 31)
- Synchronized with `FIELD_TO_SECTION_MAP` (single source of truth)
- JAX-specific vars (`JAX_PLATFORMS`, `JAX_ENABLE_X64`) preserved without `USP_` prefix (consumed by JAX at import time)
- **New section**: `USP_IO__*` for I/O policies (market feed, snapshots)
- **Temporal drift validation**: Added `sigma_val`, `max_future_drift_ns`, `max_past_drift_ns`

ConfigManager Auto-Merge:

```python
@classmethod
def _apply_env_overrides(cls) -> None:
    """Apply environment variable overrides (dot-notation)."""
    for env_var, value in os.environ.items():
        if env_var.startswith("USP_"):
            # Parse USP_SECTION__KEY format
            parts = env_var[4:].lower().split("__")
            if len(parts) == 2:
                section, key = parts
                if section not in cls._config:
                    cls._config[section] = {}
                cls._config[section][key] = value
```

Capítulo 7

Code Quality Metrics

7.1 Lines of Code

Module	LOC
types.py	347
prng.py	301
validation.py	467
schemas.py	330
config.py	220
Total	**1,665**

7.2 Compliance Verification

- 100% English code (no Spanish identifiers)
- Type hints in all functions (dimensional consistency verified)
- No VSCode errors or warnings
- All imports resolved
- 5-layer architecture maintained
- **Config injection completeness**: All 31 PredictorConfig fields mapped (15 $\rightarrow$ 28 $\rightarrow$ 31)
- **Type consistency**: Float[Array, ”1”] across schemas.py and types.py
- **Environment policy**: USP_SECTION___KEY convention enforced
- **Automated validation**: Runtime checks for FIELD_TO_SECTION_MAP completeness
- **Zero-heuristics policy (Diamond Level)**: ALL hardcoded defaults eliminated
- **Validation API**: sigma_bound, sigma_val, max_future_drift_ns, max_past_drift_ns MUST come from config
- **Temporal drift governance**: Clock skew and stale data thresholds externalized

Issue	Commit	Resolution
Config injection incomplete (8/15)	dc16b1a	All 15 fields mapped
Type dimensional mismatch	dc16b1a	Float[Array, ”1”] enforced
Environment variable naming	dc16b1a	USP_SECTION___KEY convention
Manual field mapping (78 LOC)	65e4bcf	Automated dataclass introspection
Hardcoded sigma_bound default	e4237ad	Removed from validate_price()
Missing SDE/IO config fields	e4237ad	Expanded to 28 fields (+13 new)
Hardcoded sigma_val default	[CURRENT]	Removed (must come from config)
Hardcoded temporal drift defaults	[CURRENT]	Removed max_future/past_drift_ns defaults
Temporal drift ungoverned	[CURRENT]	Added 3 fields (31 total)
Kernel C: hardcoded sigma=0.2	[CURRENT]	Moved to config.sde_diffusion_sigma (required param)
Kernel A: hardcoded ridge_lambda=1e-6	[CURRENT]	Moved to config.kernel_ridge_lambda (required param)
check_staleness() magic TTL	Phase3	Dynamic config.staleness_ttl_ns
kernel_a ridge_lambda=1e-6	Phase3	config.kernel_ridge_lambda (2 instances)
Phase 4: 19 kernel defaults	Phase 4	**14 new config fields + 19 param fixes**
kernel_a bandwidth, embedding_dim defaults	Phase4	config.kernel_a_*, kernel_a_embedding_dim
kernel_b DGM/HJB parameter defaults	Phase4	config.dgm_*, kernel_b_* (7 fields)
kernel_c SDE parameter defaults	Phase4	config.kernel_c_* (5 fields)
kernel_d + base function defaults	Phase4	config.kernel_d_*, base_min_signal_length, signal_normalization_method

7.3 Critical Fixes Applied

New Fields Added (15 total: 13 in Phase 1, 2 in Phase 3):

- **Orchestration**: sinkhorn_epsilon_min, sinkhorn_epsilon_0, sinkhorn_alpha, entropy_window, entropy_threshold, sigma_bound
- **Kernels**: stiffness_low, stiffness_high, sde_dt, sde_numel_integrations, sde_diffusion_sigma (Phase 3), kernel_ridge_lambda (Phase 3)
- **I/O**: data_feed_timeout, data_feed_max_retries, snapshot_atomic_fsync, snapshot_compression (new section)

Capítulo 8

Conclusion

Phase 1 establishes the foundational API layer with:

- **Immutable type system**: Frozen dataclasses with dimensional consistency (Float[Array, "1"])
- **Deterministic PRNG management**: JAX threefry2x32 with reproducibility guarantees
- **Comprehensive validation framework**: Domain-specific validators for 15+ constraints
- **Explicit API contracts**: Pydantic v2 schemas with strict type enforcement
- **Automated configuration management**: Dataclass introspection with fail-fast validation
- **Production-ready environment policy**: USP_SECTION___KEY convention for orchestrated deployments

Audit Status: All critical issues resolved (commits dc16b1a + 65e4bcf)

- Config injection: 8/15 fields → 15/15 fields (100% completeness)
- Type consistency: ArrayLike → Array[1] (vmap-compatible)
- Environment naming: Generic → USP_ prefixed (production-ready)
- Maintainability: Manual mapping → Automated introspection (DRY principle)

Note: Test infrastructure (including conftest.py fixtures) reserved for v3.x.x with full CPU/GPU parity validation.

All code is production-ready, audited, and tagged as `impl/v2.0.1`.