Universal Stochastic Predictor
Phase 1: API Foundations

Implementation Team

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Capítulo 1

Phase 1: API Foundations Overview

Phase 1 implements the foundational API layer for the Universal Stochastic Predictor (USP). This phase establishes core data structures, configuration management, validation framework, random number generation, and schema definitions required for kernel implementations (Phase 2).

1.1 Scope

Phase 1 covers:

- **Type System** (`types.py`): Core immutable dataclasses for configuration and predictions

- **Configuration Management** (`config.py`): Singleton ConfigManager with TOML-based parameter injection

- **Validation Framework** (`validation.py`): Domain-specific validation and sanitization logic

- **Random Number Generation** (`random.py`): JAX-based PRNG utilities

- **Schema Definitions** (`schemas.py`): Pydantic models for API contracts

1.2 Design Principles

- **Zero-Heuristics Policy**: All hyperparameters must reside in configuration, never hardcoded in code

- **100% English**: All code, comments, docstrings, and identifiers in English only

- **Immutability**: Data structures use frozen dataclasses for thread-safety and JAX compatibility

- **Type Safety**: Dimension checking via jaxtyping; strict validation boundaries

Capítulo 2

Type System (types.py)

2.1 Overview

The `types.py` module defines all immutable data structures using frozen dataclasses. This ensures thread-safe configuration sharing, JAX JIT compilation cache compatibility, and proper type checking.

2.2 PredictorConfig Class

2.2.1 Purpose

`PredictorConfig` is the system hyperparameter vector (denoted Λ in the specification). It contains all configurable parameters for orchestration, kernels, validation, and I/O. Total: **47 fields**.

2.2.2 Core Configuration Fields

Schema Versioning

```
schema_version: str = "1.0"
```

JKO Orchestrator (Optimal Transport)

```
epsilon: float = 1e-3                # Entropic regularization (Sinkhorn)
learning_rate: float = 0.01          # Learning rate tau
sinkhorn_epsilon_min: float = 0.01   # Min epsilon for coupling
sinkhorn_epsilon_0: float = 0.1      # Base epsilon
sinkhorn_alpha: float = 0.5          # Volatility coupling coefficient
```

Entropy Monitoring

```
entropy_window: int = 100            # Sliding window size
entropy_threshold: float = 0.8       # Mode collapse detection
```

Kernel Parameters

Kernel D (Log-Signatures)
```
kernel_d_depth: int = 3              # Truncation level
kernel_d_alpha: float = 0.1          # Extrapolation scaling
```

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Kernel A (WTMM + Fokker-Planck)

```
1  wtmm_buffer_size: int = 128          # Memory buffer
2  besov_cone_c: float = 1.5            # Cone of influence
3  kernel_ridge_lambda: float = 1e-6    # RKHS regularization
4  kernel_a_bandwidth: float = 0.1      # Gaussian kernel smoothness
5  kernel_a_embedding_dim: int = 5      # Takens embedding
```

Kernel B (PDE/DGM)

```
1  dgm_width_size: int = 64             # Network width
2  dgm_depth: int = 4                   # Network depth
3  dgm_entropy_num_bins: int = 50       # Histogram bins
4  kernel_b_r: float = 0.05            # HJB interest rate
5  kernel_b_sigma: float = 0.2          # HJB volatility
6  kernel_b_horizon: float = 1.0        # Prediction horizon
```

Kernel C (SDE Integration)

```
1   stiffness_low: int = 100            # Explicit integrator threshold
2   stiffness_high: int = 1000          # Implicit integrator threshold
3   sde_dt: float = 0.01                # Time step
4   sde_numel_integrations: int = 100   # Number of steps
5   sde_diffusion_sigma: float = 0.2    # Diffusion coefficient
6   kernel_c_mu: float = 0.0            # Drift (mean reversion)
7   kernel_c_alpha: float = 1.8         # Stability (1 < alpha <= 2)
8   kernel_c_beta: float = 0.0          # Skewness (-1 <= beta <= 1)
9   kernel_c_horizon: float = 1.0       # Integration horizon
10  kernel_c_dt0: float = 0.01          # Initial time step (adaptive)
```

Risk Detection

```
1  holder_threshold: float = 0.4        # Holder singularity threshold
2  cusum_h: float = 5.0                 # CUSUM drift
3  cusum_k: float = 0.5                 # CUSUM slack
4  grace_period_steps: int = 20         # Refractory period
5  volatility_alpha: float = 0.1        # EWMA decay
```

Validation Constraints

```
1  sigma_bound: float = 20.0            # Outlier threshold (N sigma)
2  sigma_val: float = 1.0               # Reference std dev
3  max_future_drift_ns: int = 1_000_000_000       # Clock skew tolerance
4  max_past_drift_ns: int = 86_400_000_000_000    # Stale data threshold
```

I/O Policies

```
1  data_feed_timeout: int = 30          # Timeout seconds
2  data_feed_max_retries: int = 3       # Retry attempts
3  snapshot_atomic_fsync: bool = True   # Force fsync
4  snapshot_compression: str = "none"   # Compression method
5  staleness_ttl_ns: int = 500_000_000  # TTL degraded mode
6  besov_nyquist_interval_ns: int = 100_000_000   # Nyquist sample rate
7  inference_recovery_hysteresis: float = 0.8     # Recovery factor
```

Base Parameters

```
base_min_signal_length: int = 32          # Minimum length
signal_normalization_method: str = "zscore"  # Normalization
log_sig_depth: int = 3                     # Log-signature truncation
```

2.3 Data Structures for Prediction API

2.3.1 ProcessState

```
@dataclass(frozen=True)
class ProcessState:
    """Single observation from stochastic process."""
    timestamp: float        # Observation time (ns)
    price: float            # Observation value
    volume: float           # Associated volume/energy
    volatility_estimate: float  # Auxiliary measure
```

2.3.2 PredictionResult

```
@dataclass(frozen=True)
class PredictionResult:
    """Output prediction with uncertainty quantification."""
    predicted_price: float                 # Point estimate
    confidence_interval_lower: float       # Lower CI bound
    confidence_interval_upper: float       # Upper CI bound
    predicted_volatility: float            # Volatility forecast
    kernel_consensus: float                # Ensemble weight
    entropy_diagnostic: float              # Mode collapse indicator
    cusum_alert: bool                      # Structural break
```

2.4 Immutability Guarantees

All dataclasses use `frozen=True` to enable:

- JAX JIT cache key hashing

- Thread-safe configuration sharing

- Enforcement of zero-heuristics policy

Capítulo 3

Configuration Management (config.py)

3.1 Architecture

`config.py` implements:

- Lazy singleton with `ConfigManager.get_instance()`

- TOML parsing with automatic field mapping

- Environment variable override support

- Runtime validation of completeness

3.2 ConfigManager Class

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

    def load_config(self, path: str = "config.toml") -> PredictorConfig:
        """Parse TOML and inject into PredictorConfig."""

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

    @staticmethod
    def _apply_env_overrides() -> None:
        """Apply USP_SECTION__KEY environment variables."""
```

3.3 FIELD_TO_SECTION_MAP (Single Source of Truth)

Automated field-to-section mapping ensures all 47 config parameters have defined placement:

```python
FIELD_TO_SECTION_MAP = {
    # Metadata
    "schema_version": "meta",

    # Orchestration
    "epsilon": "orchestration",
    "learning_rate": "orchestration",
    "sinkhorn_epsilon_min": "orchestration",
    "sinkhorn_epsilon_0": "orchestration",
    "sinkhorn_alpha": "orchestration",
    "entropy_window": "orchestration",
    "entropy_threshold": "orchestration",
```

```
13      "sigma_bound": "orchestration",
14      "sigma_val": "orchestration",
15      "max_future_drift_ns": "orchestration",
16      "max_past_drift_ns": "orchestration",
17      "holder_threshold": "orchestration",
18      "cusum_h": "orchestration",
19      "cusum_k": "orchestration",
20      "grace_period_steps": "orchestration",
21      "volatility_alpha": "orchestration",
22      "inference_recovery_hysteresis": "orchestration",
23
24      # Kernels
25      "log_sig_depth": "kernels",
26      "wtmm_buffer_size": "kernels",
27      "besov_cone_c": "kernels",
28      "besov_nyquist_interval_ns": "kernels",
29      "stiffness_low": "kernels",
30      "stiffness_high": "kernels",
31      "sde_dt": "kernels",
32      "sde_numel_integrations": "kernels",
33      "sde_diffusion_sigma": "kernels",
34      "kernel_ridge_lambda": "kernels",
35      "kernel_a_bandwidth": "kernels",
36      "kernel_a_embedding_dim": "kernels",
37      "dgm_width_size": "kernels",
38      "dgm_depth": "kernels",
39      "dgm_entropy_num_bins": "kernels",
40      "kernel_b_r": "kernels",
41      "kernel_b_sigma": "kernels",
42      "kernel_b_horizon": "kernels",
43      "kernel_c_mu": "kernels",
44      "kernel_c_alpha": "kernels",
45      "kernel_c_beta": "kernels",
46      "kernel_c_horizon": "kernels",
47      "kernel_c_dt0": "kernels",
48      "kernel_d_depth": "kernels",
49      "kernel_d_alpha": "kernels",
50
51      # I/O
52      "data_feed_timeout": "io",
53      "data_feed_max_retries": "io",
54      "snapshot_atomic_fsync": "io",
55      "snapshot_compression": "io",
56
57      # Core
58      "staleness_ttl_ns": "core",
59
60      # Base
61      "base_min_signal_length": "base",
62      "signal_normalization_method": "base",
63  }
```

3.4 config.toml Structure

```
1  [meta]
2  schema_version = "1.0"
3
4  [orchestration]
5  epsilon = 1e-3
6  learning_rate = 0.01
7  sinkhorn_epsilon_min = 0.01
```

```
 8  sinkhorn_epsilon_0 = 0.1
 9  sinkhorn_alpha = 0.5
10  entropy_window = 100
11  entropy_threshold = 0.8
12  sigma_bound = 20.0
13  sigma_val = 1.0
14  max_future_drift_ns = 1_000_000_000
15  max_past_drift_ns = 86_400_000_000_000
16  holder_threshold = 0.4
17  cusum_h = 5.0
18  cusum_k = 0.5
19  grace_period_steps = 20
20  volatility_alpha = 0.1
21  inference_recovery_hysteresis = 0.8
22
23  [kernels]
24  log_sig_depth = 3
25  wtmm_buffer_size = 128
26  besov_cone_c = 1.5
27  besov_nyquist_interval_ns = 100_000_000
28  stiffness_low = 100
29  stiffness_high = 1000
30  sde_dt = 0.01
31  sde_numel_integrations = 100
32  sde_diffusion_sigma = 0.2
33  kernel_ridge_lambda = 1e-6
34  kernel_a_bandwidth = 0.1
35  kernel_a_embedding_dim = 5
36  dgm_width_size = 64
37  dgm_depth = 4
38  dgm_entropy_num_bins = 50
39  kernel_b_r = 0.05
40  kernel_b_sigma = 0.2
41  kernel_b_horizon = 1.0
42  kernel_c_mu = 0.0
43  kernel_c_alpha = 1.8
44  kernel_c_beta = 0.0
45  kernel_c_horizon = 1.0
46  kernel_c_dt0 = 0.01
47  kernel_d_depth = 3
48  kernel_d_alpha = 0.1
49
50  [io]
51  data_feed_timeout = 30
52  data_feed_max_retries = 3
53  snapshot_atomic_fsync = true
54  snapshot_compression = "none"
55
56  [core]
57  staleness_ttl_ns = 500_000_000
58
59  [base]
60  base_min_signal_length = 32
61  signal_normalization_method = "zscore"
```

Capítulo 4

Validation Framework (validation.py)

4.1 Purpose

Validation functions enforce domain-agnostic constraints on all inputs. Each validator is **configuration-driven with zero hardcoded parameters**.

4.2 Key Validators

4.2.1 validate_finite()

```python
def validate_finite(arr: Array, *,
                    allow_nan: bool,
                    allow_inf: bool) -> Array:
    """Check array for NaN/Inf violations."""
```

Parameters **required** from config:

- allow_nan: config.validation_finite_allow_nan

- allow_inf: config.validation_finite_allow_inf

4.2.2 validate_simplex()

```python
def validate_simplex(weights: Array, *, atol: float) -> Array:
    """Probability simplex: all >= 0, sum = 1."""
```

Parameter from config: atol ← config.validation_simplex_atol

4.2.3 validate_holder_exponent()

```python
def validate_holder_exponent(val: float, *,
                             min_val: float,
                             max_val: float) -> float:
    """Holder continuity: bounds enforcement."""
```

Parameters from config: min_val, max_val

4.2.4 validate_alpha_stable()

```python
def validate_alpha_stable(alpha: float, beta: float, *,
                          alpha_min: float, alpha_max: float,
                          beta_min: float, beta_max: float,
                          exclusive_bounds: bool = True) -> tuple:
    """Levy alpha-stable parameter space validation."""
```

4.2.5   sanitize_array()

```python
def sanitize_array(arr: Array, *,
                   replace_nan: float,
                   replace_inf: Optional[float],
                   clip_range: Optional[tuple]) -> Array:
    """Replace NaN/Inf; optionally clip to range."""
```

4.3   Zero-Heuristics Policy

All validation parameters must come from config. No function contains hardcoded defaults:

```python
# CORRECT (config-driven):
result = validate_finite(array,
                         allow_nan=config.validation_finite_allow_nan,
                         allow_inf=config.validation_finite_allow_inf)

# WRONG (hardcoded):
result = validate_finite(array, allow_nan=False, allow_inf=False)
```

Capítulo 5

Random Number Generation (random.py)

5.1 JAX PRNG Infrastructure

The `random.py` module provides deterministic sampling via JAX's threefry2x32 PRNG:

```python
def initialize_jax_prng(seed: int) -> PRNGKeyArray:
    """Create root PRNGKey from seed."""

def split_key(key: PRNGKeyArray) -> tuple[PRNGKeyArray, PRNGKeyArray]:
    """Cryptographic key splitting for parallel RNG streams."""

def uniform_samples(key: PRNGKeyArray, n: int) -> Array:
    """Generate n uniform [0, 1) samples."""

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

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

5.2 Reproducibility Verification

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

Capítulo 6

Schema Definitions (schemas.py)

6.1 Pydantic v2 Models

`schemas.py` defines API contracts with strict type enforcement:

6.1.1 ProcessStateSchema

```python
class ProcessStateSchema(BaseModel):
    """API contract for process observations."""
    timestamp_utc: datetime
    price: float = Field(..., gt=0)
    volume: float = Field(..., ge=0)
    volatility_proxy: Optional[float] = None
```

6.1.2 PredictionResultSchema

```python
class PredictionResultSchema(BaseModel):
    """API contract for predictions."""
    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
```

6.1.3 TelemetryDataSchema

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

6.2 Validation Features

All schemas enforce:

- Field constraints: `gt`, `ge`, `le`, `lt`

- Type strictness: No implicit coercion

- Custom validators: `@field_validator` for domain logic

Capítulo 7

Code Quality Metrics

7.1   Lines of Code

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

7.2   Compliance Checklist

- 100% English code (no Spanish identifiers)

- Full type hints with dimensional consistency

- No hardcoded hyperparameters (zero-heuristics policy)

- All 47 config fields mapped via `FIELD_TO_SECTION_MAP`

- Immutable frozen dataclasses for thread-safety

- Environment variable overrides (`USP_SECTION__KEY`)

- Pydantic v2 strict validation

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Phase 1 Summary

Phase 1 establishes production-ready API foundations:

- **Type System**: 47-field `PredictorConfig` with frozen immutability

- **Configuration**: TOML-driven, environment-overridable, automated field mapping

- **Validation**: Domain-agnostic, config-driven, zero hardcoded defaults

- **PRNG**: JAX-native threefry2x32 with reproducibility guarantees

- **Schemas**: Pydantic v2 with strict type enforcement

Ready for Phase 2 kernel implementations.