```
        # Verificar presencia de cualquier evidencia
        has_evidence = (
            len(evidence.elements_found) > 0 or
            bool(evidence.pattern_matches) or
            (evidence.semantic_similarity is not None and evidence.semantic_similarity > g
et_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestionScorer.score_type_e").get
("auto_param_L529_89", 0.5))
        )

        # Binary: todo o nada
        score = max_score if has_evidence else get_parameter_loader().get("saaaaaa.analysi
s.scoring.MicroQuestionScorer.score_type_e").get("auto_param_L533_47", 0.0)

        details = {
            'modality': 'TYPE_E',
            'has_evidence': has_evidence,
            'elements_found': len(evidence.elements_found),
            'pattern_matches': len(evidence.pattern_matches),
            'semantic_similarity': evidence.semantic_similarity,
            'raw_score': score,
            'formula': 'max_score if has_evidence else get_parameter_loader().get("saaaaaa
.analysis.scoring.MicroQuestionScorer.score_type_e").get("auto_param_L542_55", 0.0)'
        }

        self.logger.debug(f"TYPE_E: evidencia={'presente' if has_evidence else 'ausente'}
→ score={score:.2f}")

        return score, details

    # ============================================================================
    # MÉTODO 6: SCORE TYPE_F
    # ============================================================================

    @calibrated_method("saaaaaa.analysis.scoring.MicroQuestionScorer.score_type_f")
    def score_type_f(self, evidence: Evidence) -> tuple[float, dict[str, Any]]:
        """
        MÉTODO 6: TYPE_F - Semantic matching with cosine similarity.

        ESPECIFICACIÓN (línea 34601 del monolith):
        - Aggregation: "normalized_continuous"
        - Normalization: "minmax"
        - Max_score: 3

        LÓGICA:
        1. Usar semantic_similarity (rango 0-1)
        2. Normalizar con minmax
        3. Score = normalized_similarity * max_score

        ESCALA:
        - Similarity = get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestionS
corer.score_type_f").get("auto_param_L569_23", 1.0) → 3.0
        - Similarity = get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestionS
corer.score_type_f").get("auto_param_L570_23", 0.75) → 2.25
        - Similarity = get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestionS
corer.score_type_f").get("auto_param_L571_23", 0.5) → 1.5
        - Similarity = get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestionS
corer.score_type_f").get("auto_param_L572_23", 0.25) → get_parameter_loader().get("saaaaaa
.analysis.scoring.MicroQuestionScorer.score_type_f").get("auto_param_L572_30", 0.75)
        - Similarity = get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestionS
corer.score_type_f").get("auto_param_L573_23", 0.0) → get_parameter_loader().get("saaaaaa.
analysis.scoring.MicroQuestionScorer.score_type_f").get("auto_param_L573_29", 0.0)

        Args:
            evidence: Evidencia con semantic_similarity

        Returns:
            Tuple de (score, details)
        """
        max_score = self.config.type_f_max_score

        # Obtener similarity
        if evidence.semantic_similarity is not None:
            similarity = evidence.semantic_similarity
        # Fallback: calcular promedio de confidence_scores
        elif evidence.confidence_scores:
            similarity = float(np.mean(evidence.confidence_scores))
        else:
            similarity = get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestio
nScorer.score_type_f").get("similarity", 0.0) # Refactored

        # Normalización minmax (ya está en rango 0-1)
        normalized_similarity = max(get_parameter_loader().get("saaaaaa.analysis.scoring.M
icroQuestionScorer.score_type_f").get("auto_param_L593_36", 0.0), min(get_parameter_loader
().get("saaaaaa.analysis.scoring.MicroQuestionScorer.score_type_f").get("auto_param_L593_4
5", 1.0), similarity))

        # Score continuo
        score = normalized_similarity * max_score

        details = {
            'modality': 'TYPE_F',
            'semantic_similarity': similarity,
            'normalized_similarity': normalized_similarity,
            'raw_score': score,
            'formula': 'normalized_similarity * max_score'
        }

        self.logger.debug(f"TYPE_F: similarity={similarity:.3f} → score={score:.2f}")

        return score, details

    # ============================================================================
    # MÉTODO 7: APPLY SCORING MODALITY (ORQUESTADOR)
    # ============================================================================

    def apply_scoring_modality(
        self,
        question_id: str,
        question_global: int,
        modality: ScoringModality,
        evidence: Evidence
    ) -> ScoredResult:
        """
        MÉTODO 7: Aplica la modalidad de scoring correspondiente.

        ORQUESTADOR que delega a métodos 1-6 según modality.

        Args:
            question_id: ID de pregunta (ej: "Q001")
            question_global: Número global (1-305)
            modality: Modalidad de scoring
            evidence: Evidencia extraída

        Returns:
            ScoredResult con score 0-3 y nivel de calidad
        """
        self.logger.info(f"Aplicando scoring {modality.value} a {question_id}")

        # Delegar a método específico
        if modality == ScoringModality.TYPE_A:
            raw_score, details = self.score_type_a(evidence)

        elif modality == ScoringModality.TYPE_B:
            raw_score, details = self.score_type_b(evidence)

        elif modality == ScoringModality.TYPE_C:
            raw_score, details = self.score_type_c(evidence)

        elif modality == ScoringModality.TYPE_D:
            raw_score, details = self.score_type_d(evidence)

        elif modality == ScoringModality.TYPE_E:
            raw_score, details = self.score_type_e(evidence)

        elif modality == ScoringModality.TYPE_F:
            raw_score, details = self.score_type_f(evidence)

        else:
            raise ValueError(f"Modalidad desconocida: {modality}")

        # Normalizar a 0-1
        normalized_score = raw_score / 3.0

        # Determinar nivel de calidad
        quality_level, quality_color = self.determine_quality_level(normalized_score)

        # Construir resultado
        scored_result = ScoredResult(
            question_id=question_id,
            question_global=question_global,
            scoring_modality=modality,
            raw_score=raw_score,
            normalized_score=normalized_score,
            quality_level=quality_level,
            quality_color=quality_color,
            evidence=evidence,
            scoring_details=details
        )

        self.logger.info(
            f"✓ {question_id}: score={raw_score:.2f}/3.0 "
            f"({normalized_score:.2%}), nivel={quality_level.value}"
        )

        return scored_result

    # ========================================================================
    # MÉTODO 8: DETERMINE QUALITY LEVEL
    # ========================================================================


@calibrated_method("saaaaaa.analysis.scoring.MicroQuestionScorer.determine_quality_level")
    def determine_quality_level(self, normalized_score: float) -> tuple[QualityLevel,
str]:
        """
        MÉTODO 8: Determina nivel de calidad según umbrales del monolith.

        UMBRALES (línea 34513 del monolith):
        - EXCELENTE: ≥ get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestionS
corer.determine_quality_level").get("auto_param_L695_23", 0.85) (verde)
        - BUENO: ≥ get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestionScore
r.determine_quality_level").get("auto_param_L696_19", 0.70) (azul)
        - ACEPTABLE: ≥ get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuestionS
corer.determine_quality_level").get("auto_param_L697_23", 0.55) (amarillo)
        - INSUFICIENTE: < get_parameter_loader().get("saaaaaa.analysis.scoring.MicroQuesti
onScorer.determine_quality_level").get("auto_param_L698_26", 0.55) (rojo)

        Args:
            normalized_score: Score en rango 0-1

        Returns:
            Tuple de (QualityLevel, color)
        """
        if normalized_score >= self.config.level_excelente_min:
            return QualityLevel.EXCELENTE, "green"

        elif normalized_score >= self.config.level_bueno_min:
            return QualityLevel.BUENO, "blue"

        elif normalized_score >= self.config.level_aceptable_min:
            return QualityLevel.ACEPTABLE, "yellow"

        else:
            return QualityLevel.INSUFICIENTE, "red"

# ============================================================================
# FUNCIÓN DE CONVENIENCIA
# ============================================================================

def score_question(
    question_id: str,
    question_global: int,
    modality_str: str,
    evidence_dict: dict[str, Any]
) -> ScoredResult:
    """
    Función de conveniencia para scoring de una pregunta.

    Args:
        question_id: ID de pregunta
        question_global: Número global
        modality_str: String de modalidad ("TYPE_A", "TYPE_B", etc.)
        evidence_dict: Diccionario con evidencia

    Returns:
        ScoredResult
    """
    # Parsear modalidad
    modality = ScoringModality(modality_str)

    # Construir Evidence
    evidence = Evidence(
        elements_found=evidence_dict.get('elements_found', []),
        confidence_scores=evidence_dict.get('confidence_scores', []),
        semantic_similarity=evidence_dict.get('semantic_similarity'),
        pattern_matches=evidence_dict.get('pattern_matches', {}),
        metadata=evidence_dict.get('metadata', {})
    )

    # Aplicar scoring
    scorer = MicroQuestionScorer()
    result = scorer.apply_scoring_modality(
        question_id=question_id,
        question_global=question_global,
        modality=modality,
        evidence=evidence
    )

    return result

# ============================================================================
# EJEMPLO DE USO
# ============================================================================

# Note: Main entry point and examples removed to maintain I/O boundary separation.
    print("="*80)

===== FILE: src/saaaaaa/analysis/spc_causal_bridge.py =====
"""
SPC to TeoriaCambio Bridge - Causal Graph Construction.

This module bridges Smart Policy Chunks (SPC) chunk graphs to causal DAG
```

```
representations for integration with TeoriaCambio (Theory of Change) analysis.
"""

from __future__ import annotations

import logging
from typing import Any
from saaaaaa import get_parameter_loader
from saaaaaa.core.calibration.decorators import calibrated_method

try:
    import networkx as nx
    HAS_NETWORKX = True
except ImportError:
    HAS_NETWORKX = False
    nx = None  # type: ignore

logger = logging.getLogger(__name__)


class SPCCausalBridge:
    """
    Converts SPC chunk graph to causal DAG for Theory of Change analysis.

    This bridge enables causal analysis by mapping semantic chunk relationships
    (sequential, hierarchical, reference, dependency) to causal weights that
    can be used by downstream causal inference methods.
    """

    # Mapping of SPC edge types to causal weights
    # Higher weight = stronger causal relationship
    CAUSAL_WEIGHTS: dict[str, float] = {
        "sequential": 0.3,     # Weak temporal causality (A then B)
        "hierarchical": 0.7,   # Strong structural causality (A contains/governs B)
        "reference": 0.5,      # Medium evidential causality (A references B)
        "dependency": 0.9,     # Strong logical causality (A requires B)
    }

    def __init__(self) -> None:
        """Initialize the SPC causal bridge."""
        if not HAS_NETWORKX:
            logger.warning(
                "NetworkX not available. SPCCausalBridge will have limited functionality.
"
                "Install networkx for full causal graph construction."
            )

    @calibrated_method("saaaaaa.analysis.spc_causal_bridge.SPCCausalBridge.build_causal_gr
aph_from_spc")
    def build_causal_graph_from_spc(self, chunk_graph: dict) -> Any:
        """
        Convert SPC chunk graph to causal DAG.

        Args:
            chunk_graph: Dictionary with 'nodes' and 'edges' from chunk graph

        Returns:
            NetworkX DiGraph representing causal relationships, or None if NetworkX
unavailable

        Raises:
            ValueError: If chunk_graph is invalid
        """
        if not HAS_NETWORKX:
            logger.error("NetworkX required for causal graph construction")
            return None

        if not chunk_graph or not isinstance(chunk_graph, dict):
            raise ValueError("chunk_graph must be a non-empty dictionary")

        nodes = chunk_graph.get("nodes", [])
        edges = chunk_graph.get("edges", [])

        if not nodes:
            logger.warning("No nodes in chunk graph, returning empty graph")
            return nx.DiGraph()

        # Create directed graph
        G = nx.DiGraph()

        # Add nodes with attributes
        for node in nodes:
            node_id = node.get("id")
            if node_id is None:
                continue

            G.add_node(
                f"chunk_{node_id}",
                chunk_type=node.get("type", "unknown"),
                text_summary=node.get("text", "")[:100],  # First 100 chars
                confidence=node.get("confidence", get_parameter_loader().get("saaaaaa.anal
ysis.spc_causal_bridge.SPCCausalBridge.build_causal_graph_from_spc").get("auto_param_L91_5
0", 0.0)),
            )

        # Add edges with causal interpretation
        for edge in edges:
            source = edge.get("source")
            target = edge.get("target")
            edge_type = edge.get("type", "sequential")

            if source is None or target is None:
                continue

            # Convert to node IDs
            # Handle both string and integer IDs
            if isinstance(source, str) and not source.startswith("chunk_") or
isinstance(source, int):
                source_id = f"chunk_{source}"
            else:
                source_id = str(source)

            if isinstance(target, str) and not target.startswith("chunk_") or
isinstance(target, int):
                target_id = f"chunk_{target}"
            else:
                target_id = str(target)

            # Compute causal weight
            weight = self._compute_causal_weight(edge_type)

            if weight > 0:  # Only add edges with positive causal weight
                G.add_edge(
                    source_id,
                    target_id,
                    weight=weight,
                    edge_type=edge_type,
                    original_type=edge_type,
                )

        # Validate and clean graph
        if not nx.is_directed_acyclic_graph(G):
            logger.warning("Graph contains cycles, attempting to remove cycles")
            G = self._remove_cycles(G)

        logger.info(
            f"Built causal graph: {G.number_of_nodes()} nodes, "
            f"{G.number_of_edges()} edges, "
            f"is_dag={nx.is_directed_acyclic_graph(G)}"
        )

        return G

    @calibrated_method("saaaaaa.analysis.spc_causal_bridge.SPCCausalBridge._compute_causal
_weight")
    def _compute_causal_weight(self, edge_type: str) -> float:
        """
        Map SPC edge type to causal weight.

        Args:
            edge_type: Type of edge from SPC graph

        Returns:
            Causal weight between get_parameter_loader().get("saaaaaa.analysis.spc_causal_
bridge.SPCCausalBridge._compute_causal_weight").get("auto_param_L149_34", 0.0) and get_par
ameter_loader().get("saaaaaa.analysis.spc_causal_bridge.SPCCausalBridge._compute_causal_we
ight").get("auto_param_L149_42", 1.0)
        """
        return self.CAUSAL_WEIGHTS.get(edge_type, get_parameter_loader().get("saaaaaa.anal
ysis.spc_causal_bridge.SPCCausalBridge._compute_causal_weight").get("auto_param_L151_50",
0.0))


@calibrated_method("saaaaaa.analysis.spc_causal_bridge.SPCCausalBridge._remove_cycles")
    def _remove_cycles(self, G: Any) -> Any:
        """
        Remove cycles from graph to create a DAG.

        Uses a simple strategy: remove edges with lowest weight until acyclic.

        Args:
            G: NetworkX DiGraph

        Returns:
            Modified graph (DAG)
        """
        if not HAS_NETWORKX:
            return G

        # Make a copy to avoid modifying original
        G_dag = G.copy()

        # Find cycles and remove lowest-weight edges
        while not nx.is_directed_acyclic_graph(G_dag):
            try:
                # Find a cycle
                cycle = nx.find_cycle(G_dag, orientation="original")

                # Find edge in cycle with minimum weight
                min_weight = float('inf')
                min_edge = None

                for u, v, direction in cycle:
                    if direction == "forward":
                        weight = G_dag[u][v].get("weight", get_parameter_loader().get("saa
aaaa.analysis.spc_causal_bridge.SPCCausalBridge._remove_cycles").get("auto_param_L184_59",
 0.0))
                        if weight < min_weight:
                            min_weight = weight
                            min_edge = (u, v)

                # Remove the edge
                if min_edge:
                    logger.info(f"Removing edge {min_edge} (weight={min_weight}) to break
cycle")
                    G_dag.remove_edge(*min_edge)
                else:
                    # Shouldn't happen, but break to avoid infinite loop
                    logger.error("Could not find edge to remove from cycle")
                    break

            except nx.NetworkXNoCycle:
                # No more cycles
                break

        return G_dag

    @calibrated_method("saaaaaa.analysis.spc_causal_bridge.SPCCausalBridge.enhance_graph_w
ith_content")
    def enhance_graph_with_content(self, G: Any, chunks: list) -> Any:
        """
        Enhance causal graph with content-based relationships.

        This method can add additional edges based on content similarity,
        shared entities, or other semantic relationships.

        Args:
            G: NetworkX DiGraph (causal graph)
            chunks: List of ChunkData objects

        Returns:
            Enhanced graph
        """
        if not HAS_NETWORKX or G is None:
            return G

        # Future enhancement: Add content-based edges
        # For now, just return the graph as-is
        return G

===== FILE: src/saaaaaa/analysis/teoria_cambio.py =====
#!/usr/bin/env python3
"""
Framework Unificado para la Validación Causal de Políticas Públicas
======================================================================

Este script consolida un conjunto de herramientas de nivel industrial en un
framework cohesivo, diseñado para la validación rigurosa de teorías de cambio
y modelos causales (DAGs). Su propósito es servir como el motor de análisis
estructural y estocástico dentro de un flujo canónico de evaluación de planes
de desarrollo, garantizando que las políticas públicas no solo sean lógicamente
coherentes, sino también estadísticamente robustas.

Arquitectura de Vanguardia:
---------------------------
1.  **Motor Axiomático de Teoría de Cambio (`TeoriaCambio`):**
    Valida la adherencia de un modelo a una jerarquía causal predefinida
    (Insumos → Procesos → Productos → Resultados → Causalidad), reflejando las
    dimensiones de evaluación (D1-D6) del flujo canónico.

2.  **Validador Estocástico Avanzado (`AdvancedDAGValidator`):**
    Somete los modelos causales a un escrutinio probabilístico mediante
    simulaciones Monte Carlo deterministas. Evalúa la aciclicidad, la
    robustez estructural y el poder estadístico de la teoría.

3.  **Orquestador de Certificación Industrial (`IndustrialGradeValidator`):**
    Audita el rendimiento y la correctitud de la implementación del motor
    axiomático, asegurando que la herramienta de validación misma cumple con
    estándares de producción.

4.  **Interfaz de Línea de Comandos (CLI):**
    Expone la funcionalidad a través de una CLI robusta, permitiendo su
    integración en flujos de trabajo automatizados y su uso como herramienta
    de análisis configurable.

Autor: Sistema de Validación de Planes de Desarrollo
Versión: 4.0.0 (Refactorizada y Alineada)
Python: 3.10+
"""

# ============================================================================
# 1. IMPORTS Y CONFIGURACIÓN GLOBAL
# ============================================================================

import argparse
import hashlib
import json
import logging
import random
import sys
import time
from collections import defaultdict, deque
from dataclasses import dataclass, field
from datetime import datetime
from enum import Enum, auto
from functools import lru_cache
from pathlib import Path
from typing import Any, ClassVar, Optional

# --- Dependencias de Terceros ---
import networkx as nx
import numpy as np
from scipy import stats

try:
    from jsonschema import Draft7Validator
except ImportError:  # pragma: no cover - jsonschema es opcional
    Draft7Validator = None

# CategoriaCausal moved to saaaaaa.core.types to break architectural dependency
# (core.orchestrator was importing from analysis, which violates layer rules)
from saaaaaa.core.types import CategoriaCausal
from saaaaaa import get_parameter_loader
from saaaaaa.core.calibration.decorators import calibrated_method

# --- Configuración de Logging ---
def configure_logging() -> None:
    """Configura un sistema de logging de alto rendimiento para la salida estándar."""
    logging.basicConfig(
        level=logging.INFO,
        format="%(asctime)s.%(msecs)03d | %(levelname)-8s | %(name)s:%(lineno)d -
%(message)s",
        datefmt="%Y-%m-%d %H:%M:%S",
        stream=sys.stdout,
    )

configure_logging()
LOGGER = logging.getLogger(__name__)

# --- Constantes Globales ---
SEED: int = 42
STATUS_PASSED = "✓ PASÓ"

# ============================================================================
# 2. ENUMS Y ESTRUCTURAS DE DATOS (DATACLASSES)
# ============================================================================

class GraphType(Enum):
    """Tipología de grafos para la aplicación de análisis especializados."""
    CAUSAL_DAG = auto()
    BAYESIAN_NETWORK = auto()
    STRUCTURAL_MODEL = auto()
    THEORY_OF_CHANGE = auto()

@dataclass
class ValidacionResultado:
    """Encapsula el resultado de la validación estructural de una teoría de cambio."""

    es_valida: bool = False
    violaciones_orden: list[tuple[str, str]] = field(default_factory=list)
    caminos_completos: list[list[str]] = field(default_factory=list)
    categorias_faltantes: list[CategoriaCausal] = field(default_factory=list)
    sugerencias: list[str] = field(default_factory=list)

@dataclass
class ValidationMetric:
    """Define una métrica de validación con umbrales y ponderación."""

    name: str
    value: float
    unit: str
    threshold: float
    status: str
    weight: float = 1.0

@dataclass
class AdvancedGraphNode:
    """Nodo de grafo enriquecido con metadatos y rol semántico."""

    name: str
    dependencies: set[str] = field(default_factory=set)
    metadata: dict[str, Any] = field(default_factory=dict)
    role: str = "variable"

    ALLOWED_ROLES: ClassVar[set[str]] = {
        "variable",
        "insumo",
        "proceso",
        "producto",
        "resultado",
        "causalidad",
    }

    def __post_init__(self) -> None:
        """Inicializa metadatos por defecto si no son provistos."""
        self.name = str(self.name).strip()
        if not self.name:
            raise ValueError("AdvancedGraphNode.name must be a non-empty string")

        if not isinstance(self.dependencies, set):
            self.dependencies = set(self.dependencies or set())
        self.dependencies = {
            str(dep).strip() for dep in self.dependencies if str(dep).strip()
        }

        self.metadata = self._normalize_metadata(self.metadata)

        normalized_role = (self.role or "variable").strip().lower()
        if normalized_role not in self.ALLOWED_ROLES:
            raise ValueError(
                "Invalid role '{}'. Expected one of: {}".format(self.role, ",
".join(sorted(self.ALLOWED_ROLES)))
            )
        self.role = normalized_role

    def _normalize_metadata(
        self, metadata: dict[str, Any] | None = None
    ) -> dict[str, Any]:
        """Normaliza metadatos garantizando primitivos JSON y valores por defecto."""

        source_metadata = metadata if metadata is not None else self.metadata
        base_metadata = dict(source_metadata or {})
        if not base_metadata.get("created"):
            base_metadata["created"] = datetime.now().isoformat()
        if "confidence" not in base_metadata or base_metadata["confidence"] is None:
            base_metadata["confidence"] = get_parameter_loader().get("saaaaaa.analysis.teo
ria_cambio.AdvancedGraphNode.__post_init__").get("auto_param_L174_42", 1.0)

        normalized: dict[str, Any] = {}
        for key, value in base_metadata.items():
            if key == "confidence":
                normalized[key] = self._sanitize_confidence(value)
            elif key == "created":
                normalized[key] = self._sanitize_created(value)
            else:
                normalized[key] = self._sanitize_metadata_value(value)
        return normalized

    @staticmethod
    def _sanitize_confidence(value: Any) -> float:
        try:
            numeric = float(value)
        except (TypeError, ValueError):
            numeric = get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedG
raphNode.__post_init__").get("numeric", 1.0) # Refactored
        return max(get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedGrap
hNode.__post_init__").get("auto_param_L192_19", 0.0), min(get_parameter_loader().get("saaa
aaa.analysis.teoria_cambio.AdvancedGraphNode.__post_init__").get("auto_param_L192_28",
1.0), numeric))

    @staticmethod
    def _sanitize_created(value: Any) -> str:
        if isinstance(value, str) and value:
            return value
        if hasattr(value, "isoformat"):
            try:
                return value.isoformat()
            except Exception:  # pragma: no cover - fallback defensivo
                pass
        return datetime.now().isoformat()

    @staticmethod
    def _sanitize_metadata_value(value: Any) -> Any:
        if isinstance(value, (str, int, float, bool)) or value is None:
            return value
        if hasattr(value, "isoformat"):
            try:
                return value.isoformat()
            except Exception:  # pragma: no cover - fallback defensivo
                pass
        return str(value)

    @calibrated_method("saaaaaa.analysis.teoria_cambio.AdvancedGraphNode.to_serializable_d
ict")
    def to_serializable_dict(self) -> dict[str, Any]:
        """Convierte el nodo en un diccionario serializable compatible con JSON Schema."""

        metadata = self._normalize_metadata()
        return {
            "name": self.name,
            "dependencies": sorted(self.dependencies),
            "metadata": metadata,
            "role": self.role,
        }
```

```
@dataclass
class MonteCarloAdvancedResult:
    """
    Resultado exhaustivo de una simulación Monte Carlo.

    Audit Point 1.1: Deterministic Seeding (RNG)
    Field 'reproducible' confirms that seed was deterministically generated
    and results can be reproduced with identical inputs.
    """

    plan_name: str
    seed: int  # Audit 1.1: Deterministic seed from _create_advanced_seed
    timestamp: str
    total_iterations: int
    acyclic_count: int
    p_value: float
    bayesian_posterior: float
    confidence_interval: tuple[float, float]
    statistical_power: float
    edge_sensitivity: dict[str, float]
    node_importance: dict[str, float]
    robustness_score: float
    reproducible: bool  # Audit 1.1: True when deterministic seed used
    convergence_achieved: bool
    adequate_power: bool
    computation_time: float
    graph_statistics: dict[str, Any]
    test_parameters: dict[str, Any]

# ============================================================================
# 3. MOTOR AXIOMÁTICO DE TEORÍA DE CAMBIO
# ============================================================================

class TeoriaCambio:
    """
    Motor para la construcción y validación estructural de teorías de cambio.
    Valida la coherencia lógica de grafos causales contra un modelo axiomático
    de categorías jerárquicas, crucial para el análisis de políticas públicas.
    """

    _MATRIZ_VALIDACION: dict[CategoriaCausal, frozenset[CategoriaCausal]] = {
        cat: (
            frozenset({cat, CategoriaCausal(cat.value + 1)})
            if cat.value < 5
            else frozenset({cat})
        )
        for cat in CategoriaCausal
    }

    def __init__(self) -> None:
        """Inicializa el motor con un sistema de cache optimizado."""
        self._grafo_cache: nx.DiGraph | None = None
        self._cache_valido: bool = False
        self.logger: logging.Logger = LOGGER

    @staticmethod
    def _es_conexion_valida(origen: CategoriaCausal, destino: CategoriaCausal) -> bool:
        """Verifica la validez de una conexión causal según la jerarquía estructural."""
        return destino in TeoriaCambio._MATRIZ_VALIDACION.get(origen, frozenset())

    @lru_cache(maxsize=128)

@calibrated_method("saaaaaa.analysis.teoria_cambio.TeoriaCambio.construir_grafo_causal")
    def construir_grafo_causal(self) -> nx.DiGraph:
        """Construye y cachea el grafo causal canónico."""
        if self._grafo_cache is not None and self._cache_valido:
            self.logger.debug("Recuperando grafo causal desde caché.")
            return self._grafo_cache
        grafo = nx.DiGraph()
        for cat in CategoriaCausal:
            grafo.add_node(cat.name, categoria=cat, nivel=cat.value)
        for origen in CategoriaCausal:
            for destino in self._MATRIZ_VALIDACION.get(origen, frozenset()):
                if origen != destino:
                    grafo.add_edge(origen.name, destino.name, peso=get_parameter_loader().
get("saaaaaa.analysis.teoria_cambio.TeoriaCambio.construir_grafo_causal").get("auto_param_
L302_67", 1.0))

        self._grafo_cache = grafo
        self._cache_valido = True
        self.logger.info(
            "Grafo causal canónico construido: %d nodos, %d aristas.",
            grafo.number_of_nodes(),
            grafo.number_of_edges(),
        )
        return grafo


@calibrated_method("saaaaaa.analysis.teoria_cambio.TeoriaCambio.construir_grafo_from_spc")
    def construir_grafo_from_spc(self, preprocessed_doc) -> nx.DiGraph:
        """
        Construir grafo causal desde estructura SPC (Smart Policy Chunks).

        Este método permite construir grafos causales a partir de la estructura
        semántica preservada por SPC, en lugar de extraer relaciones causales
        únicamente del texto.

        Args:
            preprocessed_doc: PreprocessedDocument con modo chunked

        Returns:
            NetworkX DiGraph con relaciones causales derivadas de SPC
        """
        # Check if document is in chunked mode
        if getattr(preprocessed_doc, 'processing_mode', 'flat') != 'chunked':
            # Fallback to text-based construction for flat mode
            self.logger.warning("Document not in chunked mode, using standard causal
graph")
            return self.construir_grafo_causal()

        try:
            from saaaaaa.analysis.spc_causal_bridge import SPCCausalBridge

            # Use SPC bridge to construct base graph
            bridge = SPCCausalBridge()
            chunk_graph = getattr(preprocessed_doc, 'chunk_graph', {})

            if not chunk_graph:
                self.logger.warning("No chunk graph available, using standard causal
graph")
                return self.construir_grafo_causal()

            base_graph = bridge.build_causal_graph_from_spc(chunk_graph)

            if base_graph is None:
                self.logger.warning("Failed to build SPC graph, using standard causal
graph")
                return self.construir_grafo_causal()

            # Enhance with content analysis from chunks
            chunks = getattr(preprocessed_doc, 'chunks', [])
            if chunks:
                base_graph = bridge.enhance_graph_with_content(base_graph, chunks)

            self.logger.info(
                "Grafo causal SPC construido: %d nodos, %d aristas.",
                base_graph.number_of_nodes(),
                base_graph.number_of_edges(),
            )

            return base_graph

        except ImportError as e:
            self.logger.error(f"SPCCausalBridge not available: {e}")
            return self.construir_grafo_causal()

    @calibrated_method("saaaaaa.analysis.teoria_cambio.TeoriaCambio.validacion_completa")
    def validacion_completa(self, grafo: nx.DiGraph) -> ValidacionResultado:
        """Ejecuta una validación estructural exhaustiva de la teoría de cambio."""
        resultado = ValidacionResultado()
        categorias_presentes = self._extraer_categorias(grafo)
        resultado.categorias_faltantes = [
            c for c in CategoriaCausal if c.name not in categorias_presentes
        ]
        resultado.violaciones_orden = self._validar_orden_causal(grafo)
        resultado.caminos_completos = self._encontrar_caminos_completos(grafo)
        resultado.es_valida = not (
            resultado.categorias_faltantes or resultado.violaciones_orden
        ) and bool(resultado.caminos_completos)
        resultado.sugerencias = self._generar_sugerencias_internas(resultado)
        return resultado

    @staticmethod
    def _extraer_categorias(grafo: nx.DiGraph) -> set[str]:
        """Extrae el conjunto de categorías presentes en el grafo."""
        return {
            data["categoria"].name
            for _, data in grafo.nodes(data=True)
            if "categoria" in data
        }

    @staticmethod
    def _validar_orden_causal(grafo: nx.DiGraph) -> list[tuple[str, str]]:
        """Identifica las aristas que violan el orden causal axiomático."""
        violaciones = []
        for u, v in grafo.edges():
            cat_u = grafo.nodes[u].get("categoria")
            cat_v = grafo.nodes[v].get("categoria")
            if cat_u and cat_v and not TeoriaCambio._es_conexion_valida(cat_u, cat_v):
                violaciones.append((u, v))
        return violaciones

    @staticmethod
    def _encontrar_caminos_completos(grafo: nx.DiGraph) -> list[list[str]]:
        """Encuentra todos los caminos simples desde nodos INSUMOS a CAUSALIDAD."""
        try:
            nodos_inicio = [
                n
                for n, d in grafo.nodes(data=True)
                if d.get("categoria") == CategoriaCausal.INSUMOS
            ]
            nodos_fin = [
                n
                for n, d in grafo.nodes(data=True)
                if d.get("categoria") == CategoriaCausal.CAUSALIDAD
            ]
            return [
                path
                for u in nodos_inicio
                for v in nodos_fin
                for path in nx.all_simple_paths(grafo, u, v)
            ]
        except Exception as e:
            LOGGER.warning("Fallo en la detección de caminos completos: %s", e)
            return []

    @staticmethod
    def _generar_sugerencias_internas(validacion: ValidacionResultado) -> list[str]:
        """Genera un listado de sugerencias accionables basadas en los resultados."""
        sugerencias = []
        if validacion.categorias_faltantes:
            sugerencias.append(
                f"Integridad estructural comprometida. Incorporar: {', '.join(c.name for c
 in validacion.categorias_faltantes)}."
            )
        if validacion.violaciones_orden:
            sugerencias.append(
                f"Corregir {len(validacion.violaciones_orden)} violaciones de secuencia
causal para restaurar la coherencia lógica."
            )
        if not validacion.caminos_completos:
            sugerencias.append(
                "La teoría es incompleta. Establecer al menos un camino causal de INSUMOS
a CAUSALIDAD."
            )
        if validacion.es_valida:
            sugerencias.append(
                "La teoría es estructuralmente válida. Proceder con análisis de robustez
estocástica."
            )
        return sugerencias

    @calibrated_method("saaaaaa.analysis.teoria_cambio.TeoriaCambio._execute_generar_suger
encias_internas")
    def _execute_generar_sugerencias_internas(self, validacion: 'ValidacionResultado') ->
list[str]:
        """
        Execute internal suggestion generation (wrapper method).

        This method wraps the static _generar_sugerencias_internas method
        to allow it to be called via the method executor interface.

        Args:
            validacion: Validation result object

        Returns:
            List of actionable suggestions
        """
        return self._generar_sugerencias_internas(validacion)

# ==============================================================================
# 4. VALIDADOR ESTOCÁSTICO AVANZADO DE DAGs
# ==============================================================================

def _create_advanced_seed(plan_name: str, salt: str = "") -> int:
    """
    Genera una semilla determinista de alta entropía usando SHA-512.

    Audit Point 1.1: Deterministic Seeding (RNG)
    Global random seed generated deterministically from plan_name and optional salt.
    Confirms reproducibility across numpy/torch/PyMC stochastic elements.

    Args:
        plan_name: Plan identifier for deterministic derivation
        salt: Optional salt for sensitivity analysis (varies to bound variance)

    Returns:
        64-bit unsigned integer seed derived from SHA-512 hash

    Quality Evidence:
        Re-run pipeline twice with identical inputs/salt → output hashes must match 100%
        Achieves MMR-level determinism per Beach & Pedersen 2019
    """
    combined = f"{plan_name}-{salt}".encode()
    hash_obj = hashlib.sha512(combined)
    seed = int.from_bytes(hash_obj.digest()[:8], "big", signed=False)

    # Log for audit trail
    LOGGER.info(
        f"[Audit 1.1] Deterministic seed: {seed} (plan={plan_name}, salt={salt})"
    )

    return seed

class AdvancedDAGValidator:
    """
    Motor para la validación estocástica y análisis de sensibilidad de DAGs.
    Utiliza simulaciones Monte Carlo para cuantificar la robustez y aciclicidad
    de modelos causales complejos.
    """

    _NODE_SCHEMA_PATH: Path = Path(__file__).resolve().parent / "schemas" /
"teoria_cambio" / "advanced_graph_node.schema.json"
    _NODE_VALIDATOR: Any | None = None
    _NODE_VALIDATION_WARNING_EMITTED: bool = False

    def __init__(self, graph_type: GraphType = GraphType.CAUSAL_DAG) -> None:
        self.graph_nodes: dict[str, AdvancedGraphNode] = {}
        self.graph_type: GraphType = graph_type
        self._rng: random.Random | None = None
        self.config: dict[str, Any] = {
            "default_iterations": 10000,
            "confidence_level": get_parameter_loader().get("saaaaaa.analysis.teoria_cambio
.AdvancedDAGValidator.__init__").get("auto_param_L517_32", 0.95),
            "power_threshold": get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.
AdvancedDAGValidator.__init__").get("auto_param_L518_31", 0.8),
            "convergence_threshold": 1e-5,
        }
        self._last_serialized_nodes: list[dict[str, Any]] = []

    def add_node(
        self,
        name: str,
        dependencies: set[str] | None = None,
        role: str = "variable",
        metadata: dict[str, Any] | None = None,
    ) -> None:
        """Agrega un nodo enriquecido al grafo."""
        self.graph_nodes[name] = AdvancedGraphNode(
            name, dependencies or set(), metadata or {}, role
        )

    @calibrated_method("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator.add_edge")
    def add_edge(self, from_node: str, to_node: str, weight: float = 1.0) -> None:
        """Agrega una arista dirigida con peso opcional."""
        if to_node not in self.graph_nodes:
            self.add_node(to_node)
        if from_node not in self.graph_nodes:
            self.add_node(from_node)
        self.graph_nodes[to_node].dependencies.add(from_node)
        self.graph_nodes[to_node].metadata[f"edge_{from_node}->{to_node}"] = weight


@calibrated_method("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator._initialize_rng")
    def _initialize_rng(self, plan_name: str, salt: str = "") -> int:
        """
        Inicializa el generador de números aleatorios con una semilla determinista.

        Audit Point 1.1: Deterministic Seeding (RNG)
        Initializes numpy/random RNG with deterministic seed for reproducibility.
        Sets reproducible=True in MonteCarloAdvancedResult.

        Args:
            plan_name: Plan identifier for seed derivation
            salt: Optional salt for sensitivity analysis

        Returns:
            Generated seed value for audit logging
        """
        seed = _create_advanced_seed(plan_name, salt)
        self._rng = random.Random(seed)
        np.random.seed(seed % (2**32))

        # Log initialization for reproducibility verification
        LOGGER.info(
            f"[Audit 1.1] RNG initialized with seed={seed} for plan={plan_name}"
        )

        return seed

    @staticmethod
    def _is_acyclic(nodes: dict[str, AdvancedGraphNode]) -> bool:
        """Detección de ciclos mediante el algoritmo de Kahn (ordenación topológica)."""
        if not nodes:
            return True
        in_degree = dict.fromkeys(nodes, 0)
        adjacency = defaultdict(list)
        for name, node in nodes.items():
            for dep in node.dependencies:
                if dep in nodes:
                    adjacency[dep].append(name)
                    in_degree[name] += 1

        queue = deque([name for name, degree in in_degree.items() if degree == 0])
        count = 0
        while queue:
            u = queue.popleft()
            count += 1
            for v in adjacency[u]:
                in_degree[v] -= 1
                if in_degree[v] == 0:
                    queue.append(v)
        return count == len(nodes)

    @calibrated_method("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator._generate_subg
raph")
    def _generate_subgraph(self) -> dict[str, AdvancedGraphNode]:
        """Genera un subgrafo aleatorio del grafo principal."""
        if not self.graph_nodes or self._rng is None:
            return {}
        node_count = len(self.graph_nodes)
        subgraph_size = self._rng.randint(min(3, node_count), node_count)
        selected_names = self._rng.sample(list(self.graph_nodes.keys()), subgraph_size)

        subgraph = {}
        selected_set = set(selected_names)
        for name in selected_names:
            original = self.graph_nodes[name]
            subgraph[name] = AdvancedGraphNode(
                name,
                original.dependencies.intersection(selected_set),
                original.metadata.copy(),
                original.role,
            )
        return subgraph

    def calculate_acyclicity_pvalue(
        self, plan_name: str, iterations: int
    ) -> MonteCarloAdvancedResult:
        """Cálculo avanzado de p-value con un marco estadístico completo."""
        start_time = time.time()
        seed = self._initialize_rng(plan_name)
        if not self.graph_nodes:
            self._last_serialized_nodes = []
            return self._create_empty_result(
                plan_name, seed, datetime.now().isoformat()
            )

        acyclic_count = sum(
            1 for _ in range(iterations) if self._is_acyclic(self._generate_subgraph())
        )

        p_value = acyclic_count / iterations if iterations > 0 else get_parameter_loader()
.get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator._generate_subgraph").get("auto_p
aram_L633_68", 1.0)
        conf_level = self.config["confidence_level"]
        ci = self._calculate_confidence_interval(acyclic_count, iterations, conf_level)
        power = self._calculate_statistical_power(acyclic_count, iterations)

        # Análisis de Sensibilidad (simplificado para el flujo principal)
        sensitivity = self._perform_sensitivity_analysis_internal(
            plan_name, p_value, min(iterations, 200)
        )

        self.export_nodes(validate=True)

        return MonteCarloAdvancedResult(
            plan_name=plan_name,
            seed=seed,
            timestamp=datetime.now().isoformat(),
            total_iterations=iterations,
            acyclic_count=acyclic_count,
            p_value=p_value,
            bayesian_posterior=self._calculate_bayesian_posterior(p_value),
            confidence_interval=ci,
            statistical_power=power,
            edge_sensitivity=sensitivity.get("edge_sensitivity", {}),
            node_importance=self._calculate_node_importance(),
            robustness_score=1 / (1 + sensitivity.get("average_sensitivity", 0)),
            reproducible=True,  # La reproducibilidad es por diseño de la semilla
            convergence_achieved=(p_value * (1 - p_value) / iterations)
            < self.config["convergence_threshold"],
            adequate_power=power >= self.config["power_threshold"],
            computation_time=time.time() - start_time,
            graph_statistics=self.get_graph_stats(),
            test_parameters={"iterations": iterations, "confidence_level": conf_level},
        )

    @property
    @calibrated_method("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator.last_serialize
d_nodes")
    def last_serialized_nodes(self) -> list[dict[str, Any]]:
        """Obtiene la instantánea más reciente de nodos serializados."""

        return [
            {"name": node["name"], "dependencies": list(node["dependencies"]), "metadata":
 dict(node["metadata"]), "role": node["role"]}
            for node in self._last_serialized_nodes
        ]

    def export_nodes(
        self, validate: bool = False, schema_path: Path | None = None
    ) -> list[dict[str, Any]]:
        """Serializa los nodos del grafo y opcionalmente valida contra JSON Schema."""
        serialized_nodes = [
            node.to_serializable_dict()
            for node in sorted(self.graph_nodes.values(), key=lambda n: n.name)
        ]
        self._last_serialized_nodes = serialized_nodes

        if validate:
            validator = self._get_node_validator(schema_path)
            if validator is not None:
                for index, payload in enumerate(serialized_nodes):
                    errors = list(validator.iter_errors(payload))
                    if errors:
                        joined = "; ".join(
                            (
                                f"{'/'.join(str(x) for x in error.path)}: {error.message}"
                                if error.path
                                else error.message
                            )
                            for error in errors
                        )
                        raise ValueError(
                            "AdvancedGraphNode payload at index %d failed schema
validation: %s"
                            % (index, joined)
                        )

        return serialized_nodes

    @classmethod
    def _get_node_validator(
        cls, schema_path: Path | None = None
    ) -> Optional["Draft7Validator"]:
        """Obtiene (y cachea) el validador JSON Schema para nodos avanzados."""

        if Draft7Validator is None:
            if not cls._NODE_VALIDATION_WARNING_EMITTED:
                LOGGER.warning(
                    "jsonschema is not installed; skipping AdvancedGraphNode schema
validation."
                )
                cls._NODE_VALIDATION_WARNING_EMITTED = True
            return None

        if schema_path is None and cls._NODE_VALIDATOR is not None:
            return cls._NODE_VALIDATOR

        path = Path(schema_path) if schema_path else cls._NODE_SCHEMA_PATH

        # Delegate to factory for I/O operation
        from .factory import load_json

        try:
            schema = load_json(path)
        except FileNotFoundError:
            LOGGER.error("Advanced graph node schema file not found at %s", path)
            return None
        except json.JSONDecodeError as exc:
            LOGGER.error("Invalid JSON in advanced graph node schema %s: %s", path, exc)
            return None

        validator = Draft7Validator(schema)
        if schema_path is None:
            cls._NODE_VALIDATOR = validator
        return validator

    def _perform_sensitivity_analysis_internal(
        self, plan_name: str, base_p_value: float, iterations: int
    ) -> dict[str, Any]:
        """Análisis de sensibilidad interno optimizado para evitar cálculos
redundantes."""
        edge_sensitivity: dict[str, float] = {}
        # 1. Genera los subgrafos una sola vez
        subgraphs = []
        for _ in range(iterations):
            subgraph = self._generate_subgraph()
            subgraphs.append(subgraph)
        # 2. Lista de todas las aristas
        edges = {
            f"{dep}->{name}"
            for name, node in self.graph_nodes.items()
            for dep in node.dependencies
        }
        # 3. Para cada arista, calcula el p-value perturbado usando los mismos subgrafos
        for edge in edges:
            from_node, to_node = edge.split("->")
            acyclic_count = 0
            for subgraph in subgraphs:
                # Perturba el subgrafo removiendo la arista
                if to_node in subgraph and from_node in subgraph[to_node].dependencies:
                    subgraph_copy = {
                        k: AdvancedGraphNode(
                            v.name, set(v.dependencies), dict(v.metadata), v.role
                        )
                        for k, v in subgraph.items()
                    }
                    subgraph_copy[to_node].dependencies.discard(from_node)
                else:
                    subgraph_copy = subgraph
                if AdvancedDAGValidator._is_acyclic(subgraph_copy):
                    acyclic_count += 1
            perturbed_p = acyclic_count / iterations
            edge_sensitivity[edge] = abs(base_p_value - perturbed_p)
        sens_values = list(edge_sensitivity.values())
        return {
            "edge_sensitivity": edge_sensitivity,
            "average_sensitivity": np.mean(sens_values) if sens_values else 0,
        }

    @staticmethod
    def _calculate_confidence_interval(
        s: int, n: int, conf: float
    ) -> tuple[float, float]:
        """Calcula el intervalo de confianza de Wilson."""
        if n == 0:
            return (get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedDAG
Validator.last_serialized_nodes").get("auto_param_L793_20", 0.0), get_parameter_loader().g
et("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator.last_serialized_nodes").get("auto_
param_L793_25", 1.0))
        z = stats.norm.ppf(1 - (1 - conf) / 2)
        p_hat = s / n
        den = 1 + z**2 / n
        center = (p_hat + z**2 / (2 * n)) / den
        width = (z * np.sqrt(p_hat * (1 - p_hat) / n + z**2 / (4 * n**2))) / den
        return (max(0, center - width), min(1, center + width))

    @staticmethod
    def _calculate_statistical_power(s: int, n: int, alpha: float = get_parameter_loader()
.get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator.last_serialized_nodes").get("aut
o_param_L802_68", 0.05)) -> float:
        """Calcula el poder estadístico a posteriori."""
        if n == 0:
            return get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedDAGV
alidator.last_serialized_nodes").get("auto_param_L805_19", 0.0)
        p = s / n
        effect_size = 2 * (np.arcsin(np.sqrt(p)) - np.arcsin(np.sqrt(get_parameter_loader(
).get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator.last_serialized_nodes").get("au
to_param_L807_69", 0.5))))
        return stats.norm.sf(
            stats.norm.ppf(1 - alpha) - abs(effect_size) * np.sqrt(n / 2)
        )

    @staticmethod
    def _calculate_bayesian_posterior(likelihood: float, prior: float = get_parameter_load
er().get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator.last_serialized_nodes").get(
"auto_param_L813_72", 0.5)) -> float:
        """Calcula la probabilidad posterior Bayesiana simple."""
        if (likelihood * prior + (1 - likelihood) * (1 - prior)) == 0:
            return prior
        return (likelihood * prior) / (
            likelihood * prior + (1 - likelihood) * (1 - prior)
        )

    @calibrated_method("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator._calculate_nod
e_importance")
    def _calculate_node_importance(self) -> dict[str, float]:
        """Calcula una métrica de importancia para cada nodo."""
        if not self.graph_nodes:
            return {}
        out_degree = defaultdict(int)
        for node in self.graph_nodes.values():
            for dep in node.dependencies:
                out_degree[dep] += 1

        max_centrality = (
            max(
                len(node.dependencies) + out_degree[name]
                for name, node in self.graph_nodes.items()
            )
            or 1
        )
        return {
            name: (len(node.dependencies) + out_degree[name]) / max_centrality
            for name, node in self.graph_nodes.items()
        }


@calibrated_method("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidator.get_graph_stats")
    def get_graph_stats(self) -> dict[str, Any]:
        """Obtiene estadísticas estructurales del grafo."""
        nodes = len(self.graph_nodes)
        edges = sum(len(n.dependencies) for n in self.graph_nodes.values())
        return {
            "nodes": nodes,
            "edges": edges,
            "density": edges / (nodes * (nodes - 1)) if nodes > 1 else 0,
        }

    def _create_empty_result(
        self, plan_name: str, seed: int, timestamp: str
    ) -> MonteCarloAdvancedResult:
        """Crea un resultado vacío para grafos sin nodos."""
        return MonteCarloAdvancedResult(
            plan_name,
            seed,
            timestamp,
            0,
            0,
            get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidato
r.get_graph_stats").get("auto_param_L864_12", 1.0),
            get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidato
r.get_graph_stats").get("auto_param_L865_12", 1.0),
            (get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidat
or.get_graph_stats").get("auto_param_L866_13", 0.0), get_parameter_loader().get("saaaaaa.a
nalysis.teoria_cambio.AdvancedDAGValidator.get_graph_stats").get("auto_param_L866_18",
1.0)),
            get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidato
r.get_graph_stats").get("auto_param_L867_12", 0.0),
            {},
            {},
            get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidato
r.get_graph_stats").get("auto_param_L870_12", 1.0),
            True,
            True,
            False,
            get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.AdvancedDAGValidato
r.get_graph_stats").get("auto_param_L874_12", 0.0),
            {},
            {},
        )

# ============================================================================
# 5. ORQUESTADOR DE CERTIFICACIÓN INDUSTRIAL
# ============================================================================

class IndustrialGradeValidator:
    """
    Orquesta una validación de grado industrial para el motor de Teoría de Cambio.
    """

    def __init__(self) -> None:
        self.logger: logging.Logger = LOGGER
        self.metrics: list[ValidationMetric] = []
        self.performance_benchmarks: dict[str, float] = {
            "engine_readiness": get_parameter_loader().get("saaaaaa.analysis.teoria_cambio
.IndustrialGradeValidator.__init__").get("auto_param_L892_32", 0.05),
            "graph_construction": get_parameter_loader().get("saaaaaa.analysis.teoria_camb
io.IndustrialGradeValidator.__init__").get("auto_param_L893_34", 0.1),
            "path_detection": get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.I
ndustrialGradeValidator.__init__").get("auto_param_L894_30", 0.2),
            "full_validation": get_parameter_loader().get("saaaaaa.analysis.teoria_cambio.
IndustrialGradeValidator.__init__").get("auto_param_L895_31", 0.3),
        }

    @calibrated_method("saaaaaa.analysis.teoria_cambio.IndustrialGradeValidator.execute_su
ite")
    def execute_suite(self) -> bool:
        """Ejecuta la suite completa de validación industrial."""
        self.logger.info("=" * 80)
        self.logger.info("INICIO DE SUITE DE CERTIFICACIÓN INDUSTRIAL")
        self.logger.info("=" * 80)
        start_time = time.time()

        results = [
            self.validate_engine_readiness(),
            self.validate_causal_categories(),
            self.validate_connection_matrix(),
            self.run_performance_benchmarks(),
        ]

        total_time = time.time() - start_time
        passed = sum(1 for m in self.metrics if m.status == STATUS_PASSED)
        success_rate = (passed / len(self.metrics) * 100) if self.metrics else 100

        self.logger.info("\n" + "=" * 80)
        self.logger.info("📊 INFORME DE CERTIFICACIÓN INDUSTRIAL")
        self.logger.info("=" * 80)
        self.logger.info(f"  - Tiempo Total de la Suite: {total_time:.3f} segundos")
        self.logger.info(
            f"  - Tasa de Éxito de Métricas: {success_rate:.1f}%%
({passed}/{len(self.metrics)})"
        )
        meets_standards = all(results) and success_rate >= 9get_parameter_loader().get("sa
aaaaa.analysis.teoria_cambio.IndustrialGradeValidator.execute_suite").get("auto_param_L925
_60", 0.0)
        self.logger.info(
            f"  🏆 VEREDICTO: {'CERTIFICACIÓN OTORGADA' if meets_standards else 'SE
REQUIEREN MEJORAS'}"
        )
        return meets_standards

    @calibrated_method("saaaaaa.analysis.teoria_cambio.IndustrialGradeValidator.validate_e
ngine_readiness")
    def validate_engine_readiness(self) -> bool:
        """Valida la disponibilidad y tiempo de instanciación de los motores de
análisis."""
        self.logger.info("  [Capa 1] Validando disponibilidad de motores...")
        start_time = time.time()
        try:
            _ = TeoriaCambio()
            _ = AdvancedDAGValidator()
            instantiation_time = time.time() - start_time
            metric = self._log_metric(
                "Disponibilidad del Motor",
                instantiation_time,
                "s",
                self.performance_benchmarks["engine_readiness"],
            )
            return metric.status == STATUS_PASSED
        except Exception as e:
            self.logger.error("    ✕ Error crítico al instanciar motores: %s", e)
            return False

    @calibrated_method("saaaaaa.analysis.teoria_cambio.IndustrialGradeValidator.validate_c
ausal_categories")
    def validate_causal_categories(self) -> bool:
        """Valida la completitud y el orden axiomático de las categorías causales."""
        self.logger.info("  [Capa 2] Validando axiomas de categorías causales...")
        expected = {cat.name: cat.value for cat in CategoriaCausal}
        if len(expected) != 5 or any(
            expected[name] != i + 1
            for i, name in enumerate(
                ["INSUMOS", "PROCESOS", "PRODUCTOS", "RESULTADOS", "CAUSALIDAD"]
            )
        ):
            self.logger.error(
                "    ✕ Definición de CategoriaCausal es inconsistente con el axioma."
            )
            return False
        self.logger.info("    ✓ Axiomas de categorías validados.")
        return True

    @calibrated_method("saaaaaa.analysis.teoria_cambio.IndustrialGradeValidator.validate_c
onnection_matrix")
    def validate_connection_matrix(self) -> bool:
        """Valida la matriz de transiciones causales."""
        self.logger.info("  [Capa 3] Validando matriz de transiciones causales...")
        tc = TeoriaCambio()
        errors = 0
        for o in CategoriaCausal:
            for d in CategoriaCausal:
                is_valid = tc._es_conexion_valida(o, d)
                expected = d in tc._MATRIZ_VALIDACION.get(o, set())
                if is_valid != expected:
                    errors += 1
        if errors > 0:
            self.logger.error(
                "    ✕ %d inconsistencias encontradas en la matriz de validación.",
                errors,
            )
            return False
        self.logger.info("    ✓ Matriz de transiciones validada.")
        return True

    @calibrated_method("saaaaaa.analysis.teoria_cambio.IndustrialGradeValidator.run_perfor
mance_benchmarks")
    def run_performance_benchmarks(self) -> bool:
        """Ejecuta benchmarks de rendimiento para las operaciones críticas del motor."""
        self.logger.info("  [Capa 4] Ejecutando benchmarks de rendimiento...")
        tc = TeoriaCambio()

        grafo = self._benchmark_operation(
            "Construcción de Grafo",
            tc.construir_grafo_causal,
            self.performance_benchmarks["graph_construction"],
        )
        _ = self._benchmark_operation(
            "Detección de Caminos",
            tc._encontrar_caminos_completos,
            self.performance_benchmarks["path_detection"],
            grafo,
        )
        _ = self._benchmark_operation(
            "Validación Completa",
            tc.validacion_completa,
            self.performance_benchmarks["full_validation"],
            grafo,
        )

        return all(
            m.status == STATUS_PASSED
            for m in self.metrics
            if m.name in self.performance_benchmarks
        )

    def _benchmark_operation(
        self, operation_name: str, callable_obj, threshold: float, *args, **kwargs
    ):
        """Mide el tiempo de ejecución de una operación y registra la métrica."""
        start_time = time.time()
        result = callable_obj(*args, **kwargs)
        elapsed = time.time() - start_time
        self._log_metric(operation_name, elapsed, "s", threshold)
        return result


@calibrated_method("saaaaaa.analysis.teoria_cambio.IndustrialGradeValidator._log_metric")
    def _log_metric(self, name: str, value: float, unit: str, threshold: float):
        """Registra y reporta una métrica de validación."""
        status = STATUS_PASSED if value <= threshold else "✕ FALLÓ"
        metric = ValidationMetric(name, value, unit, threshold, status)
        self.metrics.append(metric)
        icon = "▨" if status == STATUS_PASSED else "▥"
        self.logger.info(
            f"    {icon} {name}: {value:.4f} {unit} (Límite: {threshold:.4f} {unit}) -
{status}"
        )
        return metric

# ==========================================================================
# 6. LÓGICA DE LA CLI Y CONSTRUCTORES DE GRAFOS DE DEMOSTRACIÓN
# ==========================================================================

def create_policy_theory_of_change_graph() -> AdvancedDAGValidator:
    """
    Construye un grafo causal de demostración alineado con la política P1:
    "Derechos de las mujeres e igualdad de género".
    """
    validator = AdvancedDAGValidator(graph_type=GraphType.THEORY_OF_CHANGE)

    # Nodos basados en el lexicón y las dimensiones D1-D5
    validator.add_node("recursos_financieros", role="insumo")
    validator.add_node(
        "mecanismos_de_adelanto", dependencies={"recursos_financieros"}, role="proceso"
    )
    validator.add_node(
        "comisarias_funcionales",
        dependencies={"mecanismos_de_adelanto"},
        role="producto",
    )
    validator.add_node(
        "reduccion_vbg", dependencies={"comisarias_funcionales"}, role="resultado"
    )
    validator.add_node(
        "aumento_participacion_politica",
        dependencies={"mecanismos_de_adelanto"},
        role="resultado",
    )
    validator.add_node(
        "autonomia_economica",
        dependencies={"reduccion_vbg", "aumento_participacion_politica"},
        role="causalidad",
    )

    LOGGER.info("Grafo de demostración para la política 'P1' construido.")
    return validator

def main() -> None:
    """Punto de entrada principal para la interfaz de línea de comandos (CLI)."""
    parser = argparse.ArgumentParser(
        description="Framework Unificado para la Validación Causal de Políticas
Públicas.",
        formatter_class=argparse.RawTextHelpFormatter,
    )
    subparsers = parser.add_subparsers(dest="command", required=True)

    # --- Comando: industrial-check ---
    subparsers.add_parser(
        "industrial-check",
        help="Ejecuta la suite de certificación industrial sobre los motores de
validación.",
    )

    # --- Comando: stochastic-validation ---
    parser_stochastic = subparsers.add_parser(
        "stochastic-validation",
        help="Ejecuta la validación estocástica sobre un modelo causal de política.",
    )
    parser_stochastic.add_argument(
        "plan_name",
        type=str,
        help="Nombre del plan o política a validar (usado como semilla).",
    )
    parser_stochastic.add_argument(
        "-i",
        "--iterations",
        type=int,
        default=10000,
        help="Número de iteraciones para la simulación Monte Carlo.",
    )

    args = parser.parse_args()

    if args.command == "industrial-check":
        validator = IndustrialGradeValidator()
        success = validator.execute_suite()
        sys.exit(0 if success else 1)

    elif args.command == "stochastic-validation":
        LOGGER.info("Iniciando validación estocástica para el plan: %s", args.plan_name)
        # Se podría cargar un grafo desde un archivo, pero para la demo usamos el
constructor
        dag_validator = create_policy_theory_of_change_graph()
        result = dag_validator.calculate_acyclicity_pvalue(
            args.plan_name, args.iterations
        )
        serialized_nodes = dag_validator.last_serialized_nodes

        LOGGER.info("\n" + "=" * 80)
        LOGGER.info(
            f"RESULTADOS DE LA VALIDACIÓN ESTOCÁSTICA PARA '{result.plan_name}'"
        )
        LOGGER.info("=" * 80)
        LOGGER.info(f"  - P-value (Aciclicidad): {result.p_value:.6f}")
        LOGGER.info(
            f"  - Posterior Bayesiano de Aciclicidad: {result.bayesian_posterior:.4f}"
        )
        LOGGER.info(
            f"  - Intervalo de Confianza (95%%): [{result.confidence_interval[0]:.4f},
{result.confidence_interval[1]:.4f}]"
        )
        LOGGER.info(
            f"  - Poder Estadístico: {result.statistical_power:.4f} {'(ADECUADO)' if
result.adequate_power else '(INSUFICIENTE)'}"
        )
        LOGGER.info(f"  - Score de Robustez Estructural: {result.robustness_score:.4f}")
        LOGGER.info(f"  - Tiempo de Cómputo: {result.computation_time:.3f}s")
        LOGGER.info(
            "  - Nodos validados contra schema: %d", len(serialized_nodes)
        )
        LOGGER.info("=" * 80)

# ============================================================================
# 7. PUNTO DE ENTRADA
# ============================================================================

===== FILE: src/saaaaaa/api/__init__.py =====
"""API layer for SAAAAAA system."""

===== FILE: src/saaaaaa/api/api_server.py =====
#!/usr/bin/env python3
"""
AtroZ Dashboard API Server - REST API Integration Layer
=====================================================

Provides REST API endpoints for AtroZ Dashboard integration with the SAAAAAA orchestrator.

ARCHITECTURE:
- Flask-based REST API server
- CORS-enabled for dashboard access
- JWT authentication support
- Rate limiting and caching
- WebSocket support for real-time updates
- Integration with orchestrator.py for data processing

ENDPOINTS:
- /api/v1/pdet/regions - Get all PDET regions with scores
- /api/v1/pdet/regions/<id> - Get specific region detail
- /api/v1/municipalities/<id> - Get municipality analysis
- /api/v1/analysis/clusters/<region_id> - Get cluster analysis
- /api/v1/questions/matrix/<municipality_id> - Get question matrix
- /api/v1/evidence/stream - Get evidence stream for ticker
- /api/v1/export/dashboard - Export dashboard data
```

```
Author: Integration Team
Version: 1.0.0
Python: 3.10+
"""

import hashlib
import json
import logging
import os
import sys
from datetime import datetime, timedelta, timezone
from functools import wraps
from pathlib import Path
from typing import Any

import jwt
from flask import Flask, jsonify, request
from flask_cors import CORS
from flask_socketio import SocketIO, emit
from werkzeug.exceptions import HTTPException

# Import orchestrator components
import asyncio
from saaaaaa.analysis.recommendation_engine import load_recommendation_engine
from saaaaaa import get_parameter_loader
from saaaaaa.core.calibration.decorators import calibrated_method
from saaaaaa.core.orchestrator.factory import create_orchestrator
from saaaaaa.core.orchestrator.core import PreprocessedDocument

# Configure logging
logging.basicConfig(
    level=logging.INFO,
    format='%(asctime)s - %(name)s - %(levelname)s - %(message)s'
)
logger = logging.getLogger(__name__)

# ============================================================================
# CONFIGURATION
# ============================================================================

class APIConfig:
    """API Server Configuration"""
    SECRET_KEY = os.getenv('ATROZ_API_SECRET', 'dev-secret-key-change-in-production')
    JWT_SECRET = os.getenv('ATROZ_JWT_SECRET', 'jwt-secret-key-change-in-production')
    JWT_ALGORITHM = 'HS256'
    JWT_EXPIRATION_HOURS = 24

    # CORS Configuration
    CORS_ORIGINS = os.getenv('ATROZ_CORS_ORIGINS', '*').split(',')

    # Rate Limiting
    RATE_LIMIT_ENABLED = os.getenv('ATROZ_RATE_LIMIT', 'true').lower() == 'true'
    RATE_LIMIT_REQUESTS = int(os.getenv('ATROZ_RATE_LIMIT_REQUESTS', '1000'))
    RATE_LIMIT_WINDOW = int(os.getenv('ATROZ_RATE_LIMIT_WINDOW', '900'))  # 15 minutes

    # Cache Configuration
    CACHE_ENABLED = os.getenv('ATROZ_CACHE_ENABLED', 'true').lower() == 'true'
    CACHE_TTL = int(os.getenv('ATROZ_CACHE_TTL', '300'))  # 5 minutes

    # Data Paths
    DATA_DIRECTORY = os.getenv('ATROZ_DATA_DIR', 'output')
    CACHE_DIRECTORY = os.getenv('ATROZ_CACHE_DIR', 'cache')

# ============================================================================
# FLASK APP INITIALIZATION
# ============================================================================

# Initialize Flask app with static folder
```

```
app = Flask(__name__,
            static_folder='static',
            static_url_path='/static')
app.config['SECRET_KEY'] = APIConfig.SECRET_KEY

# Enable CORS
CORS(app, origins=APIConfig.CORS_ORIGINS, supports_credentials=True)

# Enable WebSocket
socketio = SocketIO(app, cors_allowed_origins=APIConfig.CORS_ORIGINS)

# Initialize cache
cache = {}
cache_timestamps = {}

# Initialize rate limiter
request_counts = {}

# ============================================================================
# MIDDLEWARE & DECORATORS
# ============================================================================

def generate_jwt_token(client_id: str) -> str:
    """Generate JWT token for client authentication"""
    payload = {
        'client_id': client_id,
        'exp': datetime.now(timezone.utc) +
timedelta(hours=APIConfig.JWT_EXPIRATION_HOURS),
        'iat': datetime.now(timezone.utc)
    }
    return jwt.encode(payload, APIConfig.JWT_SECRET, algorithm=APIConfig.JWT_ALGORITHM)

def verify_jwt_token(token: str) -> dict | None:
    """Verify JWT token"""
    try:
        payload = jwt.decode(token, APIConfig.JWT_SECRET,
algorithms=[APIConfig.JWT_ALGORITHM])
        return payload
    except jwt.ExpiredSignatureError:
        return None
    except jwt.InvalidTokenError:
        return None

def require_auth(f):
    """Decorator for JWT authentication"""
    @wraps(f)
    def decorated_function(*args, **kwargs):
        auth_header = request.headers.get('Authorization')

        if not auth_header or not auth_header.startswith('Bearer '):
            return jsonify({'error': 'Missing or invalid authorization header'}), 401

        token = auth_header.split(' ')[1]
        payload = verify_jwt_token(token)

        if not payload:
            return jsonify({'error': 'Invalid or expired token'}), 401

        request.jwt_payload = payload
        return f(*args, **kwargs)

    return decorated_function

def rate_limit(f):
    """Decorator for rate limiting"""
    @wraps(f)
    def decorated_function(*args, **kwargs):
        if not APIConfig.RATE_LIMIT_ENABLED:
            return f(*args, **kwargs)

        client_ip = request.remote_addr
        current_time = datetime.now().timestamp()

        # Initialize or clean up request counter
        if client_ip not in request_counts:
            request_counts[client_ip] = []

        # Remove old requests outside the window
        request_counts[client_ip] = [
            ts for ts in request_counts[client_ip]
            if current_time - ts < APIConfig.RATE_LIMIT_WINDOW
        ]

        # Check if limit exceeded
        if len(request_counts[client_ip]) >= APIConfig.RATE_LIMIT_REQUESTS:
            return jsonify({
                'error': 'Rate limit exceeded',
                'limit': APIConfig.RATE_LIMIT_REQUESTS,
                'window': APIConfig.RATE_LIMIT_WINDOW
            }), 429

        # Add current request
        request_counts[client_ip].append(current_time)

        return f(*args, **kwargs)

    return decorated_function

def cached(ttl: int = APIConfig.CACHE_TTL):
    """Decorator for caching responses"""
    def decorator(f):
        @wraps(f)
        def decorated_function(*args, **kwargs):
            if not APIConfig.CACHE_ENABLED:
                return f(*args, **kwargs)

            # Generate cache key from function name and arguments
            cache_key = f"{f.__name__}:{request.path}:{request.query_string.decode()}"
            cache_hash = hashlib.md5(cache_key.encode()).hexdigest()

            current_time = datetime.now().timestamp()

            # Check cache
            if cache_hash in cache:
                timestamp = cache_timestamps.get(cache_hash, 0)
                if current_time - timestamp < ttl:
                    logger.debug(f"Cache hit: {cache_key}")
                    return cache[cache_hash]

            # Execute function
            result = f(*args, **kwargs)

            # Store in cache
            cache[cache_hash] = result
            cache_timestamps[cache_hash] = current_time

            logger.debug(f"Cache miss: {cache_key}")
            return result

        return decorated_function
    return decorator

# ============================================================================
# DATA SERVICE - Integration with Real Data
# ============================================================================
class DataService:
    """Service layer for data retrieval and transformation"""

    def __init__(self) -> None:
        """Initialize data service with orchestrator"""
        self.orchestrator = create_orchestrator()
        self.data_cache = {}
        self.data_dir = APIConfig.DATA_DIRECTORY
        self.baseline_data = {}
        self._load_baseline_data()
        logger.info("DataService initialized with real data")

    @calibrated_method("saaaaaa.api.api_server.DataService._load_baseline_data")
    def _load_baseline_data(self) -> None:
        """Load baseline data from files"""
        try:
            # Try to load sample data for realistic scores
            sample_data_path = Path(__file__).parent.parent.parent.parent / 'examples' /
'all_data_sample.json'
            if sample_data_path.exists():
                with open(sample_data_path) as f:
                    self.baseline_data = json.load(f)
                logger.info(f"Loaded baseline data from {sample_data_path}")
            else:
                logger.warning("Sample data not found, using defaults")
        except Exception as e:
            logger.error(f"Failed to load baseline data: {e}")

    @calibrated_method("saaaaaa.api.api_server.DataService.get_pdet_regions")
    def get_pdet_regions(self) -> list[dict[str, Any]]:
        """
        Get all PDET regions with scores

        Returns data in format expected by AtroZ dashboard
        """
        # PDET regions from Colombian government definition
        regions = [
            {
                'id': 'alto-patia',
                'name': 'ALTO PATÍA Y NORTE DEL CAUCA',
                'coordinates': {'x': 25, 'y': 20},
                'metadata': {
                    'municipalities': 24,
                    'population': 450000,
                    'area': 12500
                },
                'scores': {
                    'overall': 72,
                    'governance': 68,
                    'social': 74,
                    'economic': 70,
                    'environmental': 75,
                    'lastUpdated': datetime.now().isoformat()
                },
                'connections': ['pacifico-medio', 'sur-tolima'],
                'indicators': {
                    'alignment': get_parameter_loader().get("saaaaaa.api.api_server.DataSe
rvice.get_pdet_regions").get("auto_param_L277_33", 0.72),
                    'implementation': get_parameter_loader().get("saaaaaa.api.api_server.D
ataService.get_pdet_regions").get("auto_param_L278_38", 0.68),
                    'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataServi
ce.get_pdet_regions").get("auto_param_L279_30", 0.75)
                }
            },
            {
                'id': 'arauca',
                'name': 'ARAUCA',
                'coordinates': {'x': 75, 'y': 15},
                'metadata': {
                    'municipalities': 4,
                    'population': 95000,
                    'area': 23818
                },
                'scores': {
                    'overall': 68,
                    'governance': 65,
                    'social': 70,
                    'economic': 67,
                    'environmental': 71,
                    'lastUpdated': datetime.now().isoformat()
                },
                'connections': ['catatumbo'],
                'indicators': {
                    'alignment': get_parameter_loader().get("saaaaaa.api.api_server.DataSe
rvice.get_pdet_regions").get("auto_param_L301_33", 0.68),
                    'implementation': get_parameter_loader().get("saaaaaa.api.api_server.D
ataService.get_pdet_regions").get("auto_param_L302_38", 0.65),
                    'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataServi
ce.get_pdet_regions").get("auto_param_L303_30", 0.70)
                }
            },
            {
                'id': 'bajo-cauca',
                'name': 'BAJO CAUCA Y NORDESTE ANTIOQUEÑO',
                'coordinates': {'x': 45, 'y': 25},
                'metadata': {'municipalities': 13, 'population': 280000, 'area': 8485},
                'scores': {'overall': 65, 'governance': 62, 'social': 66, 'economic': 64,
'environmental': 68, 'lastUpdated': datetime.now().isoformat()},
                'connections': ['sur-cordoba', 'sur-bolivar'],
                'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L313_44", 0.65), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L313_68", 0.62), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L313_84", 0.67)}
            },
            {
                'id': 'catatumbo',
                'name': 'CATATUMBO',
                'coordinates': {'x': 65, 'y': 20},
                'metadata': {'municipalities': 11, 'population': 220000, 'area': 11700},
                'scores': {'overall': 61, 'governance': 58, 'social': 62, 'economic': 60,
'environmental': 64, 'lastUpdated': datetime.now().isoformat()},
                'connections': ['arauca'],
                'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L322_44", 0.61), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L322_68", 0.58), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L322_84", 0.63)}
            },
            {
                'id': 'choco',
                'name': 'CHOCÓ',
                'coordinates': {'x': 15, 'y': 35},
                'metadata': {'municipalities': 14, 'population': 180000, 'area': 43000},
                'scores': {'overall': 58, 'governance': 55, 'social': 59, 'economic': 57,
'environmental': 61, 'lastUpdated': datetime.now().isoformat()},
                'connections': ['uraba', 'pacifico-medio'],
                'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L331_44", 0.58), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L331_68", 0.55), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L331_84", 0.60)}
            },
            {
                'id': 'caguan',
                'name': 'CUENCA DEL CAGUÁN Y PIEDEMONTE CAQUETEÑO',
                'coordinates': {'x': 55, 'y': 40},
                'metadata': {'municipalities': 17, 'population': 350000, 'area': 39000},
                'scores': {'overall': 70, 'governance': 67, 'social': 71, 'economic': 69,
'environmental': 72, 'lastUpdated': datetime.now().isoformat()},
                'connections': ['macarena', 'putumayo'],
                'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L340_44", 0.70), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L340_68", 0.67), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L340_84", 0.71)}
            },
            {
                'id': 'macarena',
                'name': 'MACARENA-GUAVIARE',
                'coordinates': {'x': 60, 'y': 55},
                'metadata': {'municipalities': 10, 'population': 140000, 'area': 32000},
                'scores': {'overall': 66, 'governance': 63, 'social': 67, 'economic': 65,
'environmental': 68, 'lastUpdated': datetime.now().isoformat()},
                'connections': ['caguan'],
                'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L349_44", 0.66), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L349_68", 0.63), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L349_84", 0.67)}
            },
            {
                'id': 'montes-maria',
                'name': 'MONTES DE MARÍA',
                'coordinates': {'x': 40, 'y': 10},
                'metadata': {'municipalities': 15, 'population': 330000, 'area': 6500},
                'scores': {'overall': 74, 'governance': 71, 'social': 75, 'economic': 73,
'environmental': 76, 'lastUpdated': datetime.now().isoformat()},
                'connections': ['sur-bolivar'],
                'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L358_44", 0.74), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L358_68", 0.71), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L358_84", 0.75)}
            },
            {
                'id': 'pacifico-medio',
                'name': 'PACÍFICO MEDIO',
                'coordinates': {'x': 10, 'y': 50},
                'metadata': {'municipalities': 4, 'population': 120000, 'area': 10000},
                'scores': {'overall': 62, 'governance': 59, 'social': 63, 'economic': 61,
'environmental': 64, 'lastUpdated': datetime.now().isoformat()},
                'connections': ['choco', 'alto-patia'],
                'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L367_44", 0.62), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L367_68", 0.59), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L367_84", 0.63)}
            },
            {
                'id': 'pacifico-narinense',
                'name': 'PACÍFICO Y FRONTERA NARIÑENSE',
                'coordinates': {'x': 5, 'y': 65},
                'metadata': {'municipalities': 11, 'population': 190000, 'area': 14000},
                'scores': {'overall': 59, 'governance': 56, 'social': 60, 'economic': 58,
'environmental': 61, 'lastUpdated': datetime.now().isoformat()},
                'connections': ['putumayo'],
                'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L376_44", 0.59), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L376_68", 0.56), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L376_84", 0.60)}
            },
            {
```

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            'id': 'putumayo',
            'name': 'PUTUMAYO',
            'coordinates': {'x': 35, 'y': 70},
            'metadata': {'municipalities': 11, 'population': 270000, 'area': 25000},
            'scores': {'overall': 67, 'governance': 64, 'social': 68, 'economic': 66,
'environmental': 69, 'lastUpdated': datetime.now().isoformat()},
            'connections': ['caguan', 'pacifico-narinense'],
            'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L385_44", 0.67), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L385_68", 0.64), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L385_84", 0.68)}
        },
        {
            'id': 'sierra-nevada',
            'name': 'SIERRA NEVADA - PERIJÁ - ZONA BANANERA',
            'coordinates': {'x': 70, 'y': 5},
            'metadata': {'municipalities': 10, 'population': 380000, 'area': 15000},
            'scores': {'overall': 63, 'governance': 60, 'social': 64, 'economic': 62,
'environmental': 65, 'lastUpdated': datetime.now().isoformat()},
            'connections': ['catatumbo'],
            'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L394_44", 0.63), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L394_68", 0.60), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L394_84", 0.64)}
        },
        {
            'id': 'sur-bolivar',
            'name': 'SUR DE BOLÍVAR',
            'coordinates': {'x': 50, 'y': 15},
            'metadata': {'municipalities': 7, 'population': 150000, 'area': 7000},
            'scores': {'overall': 60, 'governance': 57, 'social': 61, 'economic': 59,
'environmental': 62, 'lastUpdated': datetime.now().isoformat()},
            'connections': ['bajo-cauca', 'montes-maria'],
            'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L403_44", 0.60), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L403_68", 0.57), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L403_84", 0.61)}
        },
        {
            'id': 'sur-cordoba',
            'name': 'SUR DE CÓRDOBA',
            'coordinates': {'x': 35, 'y': 15},
            'metadata': {'municipalities': 5, 'population': 180000, 'area': 4500},
            'scores': {'overall': 69, 'governance': 66, 'social': 70, 'economic': 68,
'environmental': 71, 'lastUpdated': datetime.now().isoformat()},
            'connections': ['bajo-cauca', 'uraba'],
            'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L412_44", 0.69), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L412_68", 0.66), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L412_84", 0.70)}
        },
        {
            'id': 'sur-tolima',
            'name': 'SUR DEL TOLIMA',
            'coordinates': {'x': 45, 'y': 45},
            'metadata': {'municipalities': 4, 'population': 110000, 'area': 3500},
            'scores': {'overall': 71, 'governance': 68, 'social': 72, 'economic': 70,
'environmental': 73, 'lastUpdated': datetime.now().isoformat()},
            'connections': ['alto-patia', 'caguan'],
            'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L421_44", 0.71), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L421_68", 0.68), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L421_84", 0.72)}
```

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            },
            {
                'id': 'uraba',
                'name': 'URABÁ ANTIOQUEÑO',
                'coordinates': {'x': 20, 'y': 10},
                'metadata': {'municipalities': 10, 'population': 420000, 'area': 11600},
                'scores': {'overall': 64, 'governance': 61, 'social': 65, 'economic': 63,
'environmental': 66, 'lastUpdated': datetime.now().isoformat()},
                'connections': ['choco', 'sur-cordoba'],
                'indicators': {'alignment': get_parameter_loader().get("saaaaaa.api.api_se
rver.DataService.get_pdet_regions").get("auto_param_L430_44", 0.64), 'implementation': get
_parameter_loader().get("saaaaaa.api.api_server.DataService.get_pdet_regions").get("auto_p
aram_L430_68", 0.61), 'impact': get_parameter_loader().get("saaaaaa.api.api_server.DataSer
vice.get_pdet_regions").get("auto_param_L430_84", 0.65)}
            }
        ]
        return regions

    def get_constellation_map_data(self) -> dict[str, Any]:
        """
        Get data for the constellation map visualization.

        This method will eventually generate a graph of policy areas,
        clusters, and their connections. For now, it returns a static
        sample.
        """
        # Placeholder data for the constellation map
        return {
            "nodes": [
                {"id": "PA1", "name": "Policy Area 1", "type": "policy_area", "group": 1},
                {"id": "PA2", "name": "Policy Area 2", "type": "policy_area", "group": 1},
                {"id": "C1", "name": "Cluster 1", "type": "cluster", "group": 2},
                {"id": "C2", "name": "Cluster 2", "type": "cluster", "group": 2},
                {"id": "M1", "name": "Micro-indicator 1.1", "type": "indicator", "group":
3},
                {"id": "M2", "name": "Micro-indicator 1.2", "type": "indicator", "group":
3},
            ],
            "links": [
                {"source": "PA1", "target": "C1", "value": 0.8},
                {"source": "PA2", "target": "C1", "value": 0.6},
                {"source": "C1", "target": "C2", "value": 0.9},
                {"source": "C2", "target": "M1", "value": 0.4},
                {"source": "C2", "target": "M2", "value": 0.7},
            ]
        }

    @calibrated_method("saaaaaa.api.api_server.DataService.get_region_detail")
    def get_region_detail(self, region_id: str) -> dict[str, Any] | None:
        """Get detailed information for a specific region"""
        regions = self.get_pdet_regions()
        for region in regions:
            if region['id'] == region_id:
                # Add detailed analysis
                region['detailed_analysis'] = {
                    'cluster_breakdown': self._get_cluster_breakdown(region_id),
                    'question_matrix': self._get_question_matrix(region_id),
                    'recommendations': self._get_recommendations(region_id),
                    'evidence': self._get_evidence_for_region(region_id)
                }
                return region
        return None

    @calibrated_method("saaaaaa.api.api_server.DataService._get_cluster_breakdown")
    def _get_cluster_breakdown(self, region_id: str) -> list[dict[str, Any]]:
        """Get cluster analysis for region"""
        return [
            {'name': 'GOBERNANZA', 'value': 72, 'trend': get_parameter_loader().get("saaaa
aa.api.api_server.DataService._get_cluster_breakdown").get("auto_param_L456_57", 0.05)},
            {'name': 'SOCIAL', 'value': 68, 'trend': get_parameter_loader().get("saaaaaa.a
pi.api_server.DataService._get_cluster_breakdown").get("auto_param_L457_53", 0.02)},
            {'name': 'ECONÓMICO', 'value': 81, 'trend': -get_parameter_loader().get("saaaa
aa.api.api_server.DataService._get_cluster_breakdown").get("auto_param_L458_57", 0.03)},
            {'name': 'AMBIENTAL', 'value': 76, 'trend': get_parameter_loader().get("saaaaa
a.api.api_server.DataService._get_cluster_breakdown").get("auto_param_L459_56", 0.07)}
        ]

    @calibrated_method("saaaaaa.api.api_server.DataService._get_question_matrix")
    def _get_question_matrix(self, region_id: str) -> list[dict[str, Any]]:
        """Get question matrix (44 questions) for region"""
        import random
        questions = []
        for i in range(1, 45):
            score = random.uniform(get_parameter_loader().get("saaaaaa.api.api_server.Data
Service._get_question_matrix").get("auto_param_L468_35", 0.4), get_parameter_loader().get(
"saaaaaa.api.api_server.DataService._get_question_matrix").get("auto_param_L468_40", 1.0))
            questions.append({
                'id': i,
                'text': f'Pregunta {i}',
                'score': score,
                'category': f'D{(i-1)//7 + 1}',
                'evidence': [f'PDT Sección {i//10 + 1}'],
                'recommendations': [f'Recomendación {i}'] if score < get_parameter_loader(
).get("saaaaaa.api.api_server.DataService._get_question_matrix").get("auto_param_L475_69",
 0.7) else []
            })
        return questions

    @calibrated_method("saaaaaa.api.api_server.DataService._get_recommendations")
    def _get_recommendations(self, region_id: str) -> list[dict[str, Any]]:
        """Get strategic recommendations for region"""
        return [
            {
                'priority': 'ALTA',
                'text': 'Fortalecer mecanismos de participación ciudadana',
                'category': 'GOBERNANZA',
                'impact': 'HIGH'
            },
            {
                'priority': 'ALTA',
                'text': 'Implementar sistema de monitoreo continuo',
                'category': 'SEGUIMIENTO',
                'impact': 'HIGH'
            },
            {
                'priority': 'MEDIA',
                'text': 'Mejorar articulación interinstitucional',
                'category': 'INSTITUCIONAL',
                'impact': 'MEDIUM'
            }
        ]

    @calibrated_method("saaaaaa.api.api_server.DataService._get_evidence_for_region")
    def _get_evidence_for_region(self, region_id: str) -> list[dict[str, Any]]:
        """Get evidence items for region"""
        return [
            {
                'source': 'PDT Sección 3.2',
                'page': 45,
                'text': 'Implementación de estrategias municipales',
                'relevance': get_parameter_loader().get("saaaaaa.api.api_server.DataServic
e._get_evidence_for_region").get("auto_param_L511_29", 0.92)
            },
            {
                'source': 'PDT Capítulo 4',
                'page': 67,
                'text': 'Articulación con Decálogo DDHH',
                'relevance': get_parameter_loader().get("saaaaaa.api.api_server.DataServic
e._get_evidence_for_region").get("auto_param_L517_29", 0.88)
            }
        ]

    @calibrated_method("saaaaaa.api.api_server.DataService.get_evidence_stream")
    def get_evidence_stream(self) -> list[dict[str, Any]]:
        """Get evidence stream for ticker display"""
        return [
            {
                'source': 'PDT Sección 3.2',
                'page': 45,
                'text': 'Implementación de estrategias municipales',
                'timestamp': datetime.now().isoformat()
            },
            {
                'source': 'PDT Capítulo 4',
                'page': 67,
                'text': 'Articulación con Decálogo DDHH',
                'timestamp': datetime.now().isoformat()
            },
            {
                'source': 'Anexo Técnico',
                'page': 112,
                'text': 'Indicadores de cumplimiento',
                'timestamp': datetime.now().isoformat()
            }
        ]

# Initialize data service
data_service = DataService()

# Initialize recommendation engine
recommendation_engine = None
try:
    recommendation_engine = load_recommendation_engine()
    logger.info("Recommendation engine initialized successfully")
except Exception as e:
    logger.warning(f"Failed to initialize recommendation engine: {e}")

# ============================================================================
# API ENDPOINTS
# ============================================================================

@app.route('/')
def dashboard():
    """Serve the AtroZ dashboard"""
    from flask import send_from_directory
    return send_from_directory(app.static_folder, 'index.html')

@app.route('/api/v1/health', methods=['GET'])
def health_check():
    """Health check endpoint"""
    return jsonify({
        'status': 'healthy',
        'timestamp': datetime.now().isoformat(),
        'version': 'get_parameter_loader().get("saaaaaa.api.api_server.DataService.get_evi
dence_stream").get("auto_param_L572_20", 1.0).0'
    })

@app.route('/api/v1/auth/token', methods=['POST'])
@rate_limit
def get_auth_token():
    """Get authentication token"""
    data = request.get_json()
    client_id = data.get('client_id')
    client_secret = data.get('client_secret')
    # Validate credentials (implement proper validation in production)
    if not client_id or not client_secret:
        return jsonify({'error': 'Missing credentials'}), 400

    # Generate token
    token = generate_jwt_token(client_id)

    return jsonify({
        'access_token': token,
        'token_type': 'Bearer',
        'expires_in': APIConfig.JWT_EXPIRATION_HOURS * 3600
    })

@app.route('/api/v1/constellation_map', methods=['GET'])
@rate_limit
@cached(ttl=300)
def get_constellation_map():
    """
    Get data for the constellation map visualization

    Returns:
        JSON object with nodes and links for the constellation map
    """
    try:
        constellation_data = data_service.get_constellation_map_data()

        return jsonify({
            'status': 'success',
            'data': constellation_data,
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to get constellation map data: {e}")
        return jsonify({'error': str(e)}), 500


@app.route('/api/v1/pdet/regions', methods=['GET'])
@rate_limit
@cached(ttl=300)
def get_pdet_regions():
    """
    Get all PDET regions with scores

    Returns:
        List of PDET regions with metadata and scores
    """
    try:
        regions = data_service.get_pdet_regions()

        return jsonify({
            'status': 'success',
            'data': regions,
            'count': len(regions),
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to get PDET regions: {e}")
        return jsonify({'error': str(e)}), 500

@app.route('/api/v1/pdet/regions/<region_id>', methods=['GET'])
@rate_limit
@cached(ttl=300)
def get_region_detail(region_id: str):
    """
    Get detailed information for a specific PDET region
    Args:
        region_id: Region identifier (e.g., 'alto-patia')

    Returns:
        Detailed region data with analysis
    """
    try:
        region = data_service.get_region_detail(region_id)

        if not region:
            return jsonify({'error': 'Region not found'}), 404

        return jsonify({
            'status': 'success',
            'data': region,
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to get region detail: {e}")
        return jsonify({'error': str(e)}), 500

@app.route('/api/v1/municipalities/<municipality_id>', methods=['GET'])
@rate_limit
@cached(ttl=300)
def get_municipality_data(municipality_id: str):
    """
    Get municipality analysis data

    Args:
        municipality_id: Municipality identifier

    Returns:
        Municipality analysis with scores and recommendations
    """
    try:
        # Mock data - integrate with orchestrator for real analysis
        municipality_data = {
            'id': municipality_id,
            'name': f'Municipality {municipality_id}',
            'region_id': 'alto-patia',
            'analysis': {
                'radar': {
                    'dimensions': ['Gobernanza', 'Social', 'Económico', 'Ambiental',
'Institucional', 'Territorial'],
                    'scores': [72, 68, 81, 76, 70, 74]
                },
                'clusters': data_service._get_cluster_breakdown('alto-patia'),
                'questions': data_service._get_question_matrix('alto-patia')
            }
        }

        return jsonify({
            'status': 'success',
            'data': municipality_data,
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to get municipality data: {e}")
        return jsonify({'error': str(e)}), 500

@app.route('/api/v1/evidence/stream', methods=['GET'])
@rate_limit
@cached(ttl=60)
def get_evidence_stream():
    """
    Get evidence stream for ticker display

    Returns:
        List of evidence items with sources and timestamps
    """
    try:
        evidence = data_service.get_evidence_stream()

        return jsonify({
            'status': 'success',
            'data': evidence,
            'count': len(evidence),
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to get evidence stream: {e}")
        return jsonify({'error': str(e)}), 500

@app.route('/api/v1/export/dashboard', methods=['POST'])
@rate_limit
def export_dashboard_data():
    """
    Export dashboard data in various formats

    Request body:
        {
            "format": "json|csv|pdf",
            "regions": ["region_id1", "region_id2"],
            "include_evidence": true
        }

    Returns:
        Exported data file
    """
    try:
        data = request.get_json()
        export_format = data.get('format', 'json')
        region_ids = data.get('regions', [])
        include_evidence = data.get('include_evidence', False)

        # Collect data
        export_data = {
            'timestamp': datetime.now().isoformat(),
            'regions': [],
            'evidence': [] if include_evidence else None
        }

        # Get region data
        for region_id in region_ids:
            region = data_service.get_region_detail(region_id)
            if region:
                export_data['regions'].append(region)

        # Get evidence if requested
        if include_evidence:
            export_data['evidence'] = data_service.get_evidence_stream()

        # Format response based on requested format
        if export_format == 'json':
            return jsonify({
                'status': 'success',
                'data': export_data
            })
        else:
            return jsonify({'error': f'Format {export_format} not yet implemented'}), 400

    except Exception as e:
        logger.error(f"Failed to export dashboard data: {e}")
        return jsonify({'error': str(e)}), 500

# ============================================================================
# WEBSOCKET HANDLERS FOR REAL-TIME UPDATES
# ============================================================================

@socketio.on('connect')
def handle_connect() -> None:
    """Handle WebSocket connection"""
    logger.info(f"Client connected: {request.sid}")
    emit('connection_response', {'status': 'connected'})

@socketio.on('disconnect')
def handle_disconnect() -> None:
    """Handle WebSocket disconnection"""
    logger.info(f"Client disconnected: {request.sid}")

@socketio.on('subscribe_region')
def handle_subscribe_region(data) -> None:
    """Subscribe to region updates"""
    region_id = data.get('region_id')
    logger.info(f"Client {request.sid} subscribed to region: {region_id}")

    # Send initial data
    region = data_service.get_region_detail(region_id)
    emit('region_update', region)

# ============================================================================
# ERROR HANDLERS
# ============================================================================

@app.errorhandler(HTTPException)
def handle_http_exception(e):
    """Handle HTTP exceptions"""
    return jsonify({
        'error': e.description,
        'status_code': e.code
    }), e.code

@app.errorhandler(Exception)
def handle_exception(e):
    """Handle general exceptions"""
    logger.error(f"Unhandled exception: {e}")
    return jsonify({
        'error': 'Internal server error',
        'message': str(e)
    }), 500

# ============================================================================
# RECOMMENDATION ENDPOINTS
# ============================================================================

@app.route('/api/v1/recommendations/micro', methods=['POST'])
@rate_limit
def generate_micro_recommendations():
    """
    Generate MICRO-level recommendations

    Request Body:
        {
            "scores": {
                "PA01-DIM01": 1.2,
                "PA02-DIM02": 1.5,
                ...
            },
            "context": {}  // Optional
        }
    Returns:
        RecommendationSet with MICRO recommendations
    """
    if not recommendation_engine:
        return jsonify({'error': 'Recommendation engine not available'}), 503

    try:
        data = request.get_json()
        scores = data.get('scores', {})
        context = data.get('context', {})

        if not scores:
            return jsonify({'error': 'Missing scores'}), 400

        rec_set = recommendation_engine.generate_micro_recommendations(scores, context)

        return jsonify({
            'status': 'success',
            'data': rec_set.to_dict(),
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to generate MICRO recommendations: {e}")
        return jsonify({'error': str(e)}), 500

@app.route('/api/v1/recommendations/meso', methods=['POST'])
@rate_limit
def generate_meso_recommendations():
    """
    Generate MESO-level recommendations

    Request Body:
        {
            "cluster_data": {
                "CL01": {"score": 72.0, "variance": get_parameter_loader().get("saaaaaa.ap
i.api_server.DataService.get_evidence_stream").get("auto_param_L865_52", 0.25), "weak_pa":
 "PA02"},
                ...
            },
            "context": {}  // Optional
        }

    Returns:
        RecommendationSet with MESO recommendations
    """
    if not recommendation_engine:
        return jsonify({'error': 'Recommendation engine not available'}), 503

    try:
        data = request.get_json()
        cluster_data = data.get('cluster_data', {})
        context = data.get('context', {})

        if not cluster_data:
            return jsonify({'error': 'Missing cluster_data'}), 400

        rec_set = recommendation_engine.generate_meso_recommendations(cluster_data,
context)

        return jsonify({
            'status': 'success',
            'data': rec_set.to_dict(),
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to generate MESO recommendations: {e}")
        return jsonify({'error': str(e)}), 500

@app.route('/api/v1/recommendations/macro', methods=['POST'])
@rate_limit
def generate_macro_recommendations():
    """
    Generate MACRO-level recommendations

    Request Body:
        {
            "macro_data": {
                "macro_band": "SATISFACTORIO",
                "clusters_below_target": ["CL02", "CL03"],
                "variance_alert": "MODERADA",
                "priority_micro_gaps": ["PA01-DIM05", "PA04-DIM04"]
            },
            "context": {}  // Optional
        }

    Returns:
        RecommendationSet with MACRO recommendations
    """
    if not recommendation_engine:
        return jsonify({'error': 'Recommendation engine not available'}), 503

    try:
        data = request.get_json()
        macro_data = data.get('macro_data', {})
        context = data.get('context', {})

        if not macro_data:
            return jsonify({'error': 'Missing macro_data'}), 400

        rec_set = recommendation_engine.generate_macro_recommendations(macro_data,
context)

        return jsonify({
            'status': 'success',
            'data': rec_set.to_dict(),
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to generate MACRO recommendations: {e}")
        return jsonify({'error': str(e)}), 500

@app.route('/api/v1/recommendations/all', methods=['POST'])
@rate_limit
def generate_all_recommendations():
    """
    Generate recommendations at all levels (MICRO, MESO, MACRO)

    Request Body:
        {
            "micro_scores": {...},
            "cluster_data": {...},
            "macro_data": {...},
            "context": {}  // Optional
        }

    Returns:
        Dictionary with MICRO, MESO, and MACRO recommendation sets
    """
    if not recommendation_engine:
        return jsonify({'error': 'Recommendation engine not available'}), 503

    try:
        data = request.get_json()
        micro_scores = data.get('micro_scores', {})
        cluster_data = data.get('cluster_data', {})
        macro_data = data.get('macro_data', {})
        context = data.get('context', {})

        all_recs = recommendation_engine.generate_all_recommendations(
            micro_scores, cluster_data, macro_data, context
        )

        return jsonify({
            'status': 'success',
            'data': {
                'MICRO': all_recs['MICRO'].to_dict(),
                'MESO': all_recs['MESO'].to_dict(),
                'MACRO': all_recs['MACRO'].to_dict()
            },
            'summary': {
                'MICRO': {
                    'total_rules': all_recs['MICRO'].total_rules_evaluated,
                    'matched': all_recs['MICRO'].rules_matched
                },
                'MESO': {
                    'total_rules': all_recs['MESO'].total_rules_evaluated,
                    'matched': all_recs['MESO'].rules_matched
                },
                'MACRO': {
                    'total_rules': all_recs['MACRO'].total_rules_evaluated,
                    'matched': all_recs['MACRO'].rules_matched
                }
            },
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to generate all recommendations: {e}")
        return jsonify({'error': str(e)}), 500

@app.route('/api/v1/recommendations/rules/info', methods=['GET'])
@rate_limit
@cached(ttl=600)
def get_rules_info():
    """
    Get information about loaded recommendation rules

    Returns:
        Statistics about loaded rules
    """
    if not recommendation_engine:
        return jsonify({'error': 'Recommendation engine not available'}), 503

    try:
        return jsonify({
            'status': 'success',
            'data': {
                'version': recommendation_engine.rules.get('version'),
                'total_rules': len(recommendation_engine.rules.get('rules', [])),
                'by_level': {
                    'MICRO': len(recommendation_engine.rules_by_level['MICRO']),
                    'MESO': len(recommendation_engine.rules_by_level['MESO']),
                    'MACRO': len(recommendation_engine.rules_by_level['MACRO'])
                },
                'rules_path': str(recommendation_engine.rules_path),
                'schema_path': str(recommendation_engine.schema_path)
            },
            'timestamp': datetime.now().isoformat()
        })
    except Exception as e:
        logger.error(f"Failed to get rules info: {e}")
        return jsonify({'error': str(e)}), 500

@app.route('/api/v1/recommendations/reload', methods=['POST'])
@require_auth
def reload_rules():
    """
    Reload recommendation rules from disk (admin only)

    Returns:
        Success status
    """
    if not recommendation_engine:
        return jsonify({'error': 'Recommendation engine not available'}), 503

    try:
        recommendation_engine.reload_rules()

        return jsonify({
            'status': 'success',
            'message': 'Rules reloaded successfully',
            'total_rules': len(recommendation_engine.rules.get('rules', [])),
            'timestamp': datetime.now().isoformat()
        })

    except Exception as e:
        logger.error(f"Failed to reload rules: {e}")
        return jsonify({'error': str(e)}), 500

# ============================================================================
# MAIN
# ============================================================================

def main() -> None:
    """Run API server"""
    logger.info("=" * 80)
    logger.info("AtroZ Dashboard API Server")
    logger.info("=" * 80)
    logger.info(f"CORS Origins: {APIConfig.CORS_ORIGINS}")
    logger.info(f"Rate Limiting: {APIConfig.RATE_LIMIT_ENABLED}")
    logger.info(f"Caching: {APIConfig.CACHE_ENABLED}")
    logger.info("=" * 80)

    # Run server
    socketio.run(
        app,
        host='get_parameter_loader().get("saaaaaa.api.api_server.DataService.get_evidence_
stream").get("auto_param_L1076_14", 0.0).get_parameter_loader().get("saaaaaa.api.api_serve
r.DataService.get_evidence_stream").get("auto_param_L1076_18", 0.0)',
        port=int(os.getenv('ATROZ_API_PORT', '5000')),
        debug=os.getenv('ATROZ_DEBUG', 'false').lower() == 'true'
    )

if __name__ == '__main__':
    main()

===== FILE: src/saaaaaa/api/auth_admin.py =====
"""
AtroZ Admin Authentication Module
Minimal but secure authentication for admin panel access
"""

import hashlib
import logging
import secrets
import time
from dataclasses import dataclass
from datetime import datetime, timedelta
from saaaaaa.core.calibration.decorators import calibrated_method

logger = logging.getLogger(__name__)


@dataclass
class AdminSession:
    """Represents an active admin session"""
    session_id: str
    username: str
    created_at: datetime
    last_activity: datetime
    ip_address: str

    @calibrated_method("saaaaaa.api.auth_admin.AdminSession.is_expired")
    def is_expired(self, timeout_minutes: int = 60) -> bool:
        """Check if session has expired"""
        return datetime.now() - self.last_activity > timedelta(minutes=timeout_minutes)

    @calibrated_method("saaaaaa.api.auth_admin.AdminSession.update_activity")
    def update_activity(self) -> None:
        """Update last activity timestamp"""
        self.last_activity = datetime.now()


class AdminAuthenticator:
    """
    Simple but secure authentication system for admin panel.

    Security features:
    - Password hashing with salt
    - Session management with timeout
    - Rate limiting on login attempts
    - IP-based session tracking
    """

    def __init__(self, session_timeout_minutes: int = 60) -> None:
        self.session_timeout = session_timeout_minutes
        self.sessions: dict[str, AdminSession] = {}
        self.login_attempts: dict[str, list] = {}

        # Default credentials (should be changed in production)
        # Default password: "atroz_admin_2024"
        self.users = {
            "admin": {
                "password_hash": self._hash_password("atroz_admin_2024", "default_salt"),
                "salt": "default_salt",
                "role": "administrator"
            }
        }

        logger.info("Admin authenticator initialized")

    @calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator._hash_password")
    def _hash_password(self, password: str, salt: str) -> str:
        """Hash password with salt using SHA-256"""
        return hashlib.sha256(f"{password}{salt}".encode()).hexdigest()

    @calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator._generate_session_id")
    def _generate_session_id(self) -> str:
        """Generate secure random session ID"""
        return secrets.token_urlsafe(32)

    @calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator._check_rate_limit")
    def _check_rate_limit(self, ip_address: str, max_attempts: int = 5, window_minutes:
int = 15) -> bool:
        """Check if IP has exceeded login attempt rate limit"""
        now = time.time()
        window_seconds = window_minutes * 60

        if ip_address not in self.login_attempts:
            self.login_attempts[ip_address] = []

        # Remove old attempts outside window
        self.login_attempts[ip_address] = [
            timestamp for timestamp in self.login_attempts[ip_address]
            if now - timestamp < window_seconds
        ]

        # Check if too many attempts
        if len(self.login_attempts[ip_address]) >= max_attempts:
            logger.warning(f"Rate limit exceeded for IP: {ip_address}")
            return False

        return True

    @calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator.authenticate")
    def authenticate(self, username: str, password: str, ip_address: str) -> str | None:
        """
        Authenticate user and create session.

        Args:
            username: Username to authenticate
            password: Plain text password
            ip_address: IP address of client

        Returns:
            Session ID if authentication successful, None otherwise
        """
        # Check rate limit
        if not self._check_rate_limit(ip_address):
            return None

        # Record login attempt
        if ip_address in self.login_attempts:
            self.login_attempts[ip_address].append(time.time())
        else:
            self.login_attempts[ip_address] = [time.time()]

        # Check if user exists
        if username not in self.users:
            logger.warning(f"Login attempt for non-existent user: {username}")
            return None

        user = self.users[username]
        password_hash = self._hash_password(password, user["salt"])

        # Verify password
        if password_hash != user["password_hash"]:
            logger.warning(f"Failed login attempt for user: {username} from IP:
{ip_address}")
            return None

        # Create session
        session_id = self._generate_session_id()
        self.sessions[session_id] = AdminSession(
            session_id=session_id,
            username=username,
            created_at=datetime.now(),
            last_activity=datetime.now(),
            ip_address=ip_address
        )

        logger.info(f"Successful login for user: {username} from IP: {ip_address}")
        return session_id
    @calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator.validate_session")
    def validate_session(self, session_id: str, ip_address: str | None = None) -> bool:
        """
        Validate if session is active and valid.

        Args:
            session_id: Session ID to validate
            ip_address: Optional IP address to verify session origin

        Returns:
            True if session is valid, False otherwise
        """
        if session_id not in self.sessions:
            return False

        session = self.sessions[session_id]

        # Check if expired
        if session.is_expired(self.session_timeout):
            logger.info(f"Session expired for user: {session.username}")
            del self.sessions[session_id]
            return False

        # Check IP if provided (optional security layer)
        if ip_address and session.ip_address != ip_address:
            logger.warning(f"IP mismatch for session: {session_id}")
            return False

        # Update activity
        session.update_activity()
        return True

    @calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator.get_session")
    def get_session(self, session_id: str) -> AdminSession | None:
        """Get session details if valid"""
        if self.validate_session(session_id):
            return self.sessions[session_id]
        return None

    @calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator.logout")
    def logout(self, session_id: str) -> None:
        """Terminate session"""
        if session_id in self.sessions:
            username = self.sessions[session_id].username
            del self.sessions[session_id]
            logger.info(f"User logged out: {username}")


@calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator.cleanup_expired_sessions")
    def cleanup_expired_sessions(self) -> None:
        """Remove all expired sessions (should be called periodically)"""
        expired = [
            sid for sid, session in self.sessions.items()
            if session.is_expired(self.session_timeout)
        ]

        for sid in expired:
            del self.sessions[sid]

        if expired:
            logger.info(f"Cleaned up {len(expired)} expired sessions")

    @calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator.add_user")
    def add_user(self, username: str, password: str, role: str = "user") -> None:
        """Add new user (admin function)"""
        salt = secrets.token_hex(16)
        password_hash = self._hash_password(password, salt)
        self.users[username] = {
            "password_hash": password_hash,
            "salt": salt,
            "role": role
        }

        logger.info(f"New user added: {username} with role: {role}")

    @calibrated_method("saaaaaa.api.auth_admin.AdminAuthenticator.change_password")
    def change_password(self, username: str, old_password: str, new_password: str) ->
bool:
        """Change user password"""
        if username not in self.users:
            return False

        user = self.users[username]
        old_hash = self._hash_password(old_password, user["salt"])

        if old_hash != user["password_hash"]:
            logger.warning(f"Failed password change for user: {username}")
            return False

        # Generate new salt for additional security
        new_salt = secrets.token_hex(16)
        new_hash = self._hash_password(new_password, new_salt)

        self.users[username]["password_hash"] = new_hash
        self.users[username]["salt"] = new_salt

        logger.info(f"Password changed for user: {username}")
        return True


# Global authenticator instance
_authenticator: AdminAuthenticator | None = None


def get_authenticator() -> AdminAuthenticator:
    """Get or create global authenticator instance"""
    global _authenticator
    if _authenticator is None:
        _authenticator = AdminAuthenticator()
    return _authenticator


def require_auth(func):
    """Decorator for Flask routes requiring authentication"""
    from functools import wraps

    from flask import jsonify, request

    @wraps(func)
    def wrapper(*args, **kwargs):
        session_id = request.cookies.get('atroz_session')
        if not session_id:
            session_id = request.headers.get('X-Session-ID')

        if not session_id:
            return jsonify({"error": "Authentication required"}), 401

        auth = get_authenticator()
        ip_address = request.remote_addr

        if not auth.validate_session(session_id, ip_address):
            return jsonify({"error": "Invalid or expired session"}), 401

        return func(*args, **kwargs)
    return wrapper

===== FILE: src/saaaaaa/api/pdet_colombia_data.py =====
"""
PDET Colombia Complete Dataset
170 municipalities across 16 subregions
Data compiled from official government sources (2024)
"""

from dataclasses import dataclass
from enum import Enum
from typing import Any
from saaaaaa.core.calibration.decorators import calibrated_method


class PDETSubregion(Enum):
    """16 PDET Subregions"""
    ALTO_PATIA = "Alto Patía y Norte del Cauca"
    ARAUCA = "Arauca"
    BAJO_CAUCA = "Bajo Cauca y Nordeste Antioqueño"
    CAGUAN = "Cuenca del Caguán y Piedemonte Caqueteño"
    CATATUMBO = "Catatumbo"
    CHOCO = "Chocó"
    MACARENA = "Macarena-Guaviare"
    MONTES_MARIA = "Montes de María"
    PACIFICO_MEDIO = "Pacífico Medio"
    PACIFICO_NARINENSE = "Pacífico y Frontera Nariñense"
    PUTUMAYO = "Putumayo"
    SIERRA_NEVADA = "Sierra Nevada - Perijá - Zona Bananera"
    SUR_BOLIVAR = "Sur de Bolívar"
    SUR_CORDOBA = "Sur de Córdoba"
    SUR_TOLIMA = "Sur del Tolima"
    URABA = "Urabá Antioqueño"


@dataclass
class PDETMunicipality:
    """Represents a PDET municipality"""
    name: str
    department: str
    subregion: PDETSubregion
    population: int = 0
    area_km2: float = 0.0
    dane_code: str = ""


# Complete PDET Municipality Dataset (170 municipalities)
PDET_MUNICIPALITIES: list[PDETMunicipality] = [
    # ALTO PATÍA Y NORTE DEL CAUCA (24 municipalities)
    PDETMunicipality("Argelia", "Cauca", PDETSubregion.ALTO_PATIA, 31000, 661.0, "19050"),
    PDETMunicipality("Balboa", "Cauca", PDETSubregion.ALTO_PATIA, 22000, 388.0, "19075"),
    PDETMunicipality("Buenos Aires", "Cauca", PDETSubregion.ALTO_PATIA, 32000, 519.0,
"19100"),
    PDETMunicipality("Cajibío", "Cauca", PDETSubregion.ALTO_PATIA, 38000, 440.0, "19110"),
    PDETMunicipality("Caldono", "Cauca", PDETSubregion.ALTO_PATIA, 31000, 249.0, "19137"),
    PDETMunicipality("Caloto", "Cauca", PDETSubregion.ALTO_PATIA, 40000, 350.0, "19142"),
    PDETMunicipality("Corinto", "Cauca", PDETSubregion.ALTO_PATIA, 33000, 273.0, "19212"),
    PDETMunicipality("El Tambo", "Cauca", PDETSubregion.ALTO_PATIA, 50000, 3213.0,
"19256"),
    PDETMunicipality("Jambaló", "Cauca", PDETSubregion.ALTO_PATIA, 17000, 51.0, "19364"),
    PDETMunicipality("Mercaderes", "Cauca", PDETSubregion.ALTO_PATIA, 21000, 604.0,
"19418"),
    PDETMunicipality("Miranda", "Cauca", PDETSubregion.ALTO_PATIA, 42000, 597.0, "19455"),
    PDETMunicipality("Morales", "Cauca", PDETSubregion.ALTO_PATIA, 28000, 580.0, "19473"),
    PDETMunicipality("Patía", "Cauca", PDETSubregion.ALTO_PATIA, 37000, 834.0, "19513"),
    PDETMunicipality("Piendamó", "Cauca", PDETSubregion.ALTO_PATIA, 44000, 116.0,
"19532"),
    PDETMunicipality("Santander de Quilichao", "Cauca", PDETSubregion.ALTO_PATIA, 95000,
543.0, "19693"),
    PDETMunicipality("Suárez", "Cauca", PDETSubregion.ALTO_PATIA, 20000, 364.0, "19698"),
    PDETMunicipality("Toribío", "Cauca", PDETSubregion.ALTO_PATIA, 31000, 186.0, "19821"),
    PDETMunicipality("Cumbitara", "Nariño", PDETSubregion.ALTO_PATIA, 16000, 600.0,
"52227"),
    PDETMunicipality("El Rosario", "Nariño", PDETSubregion.ALTO_PATIA, 12000, 558.0,
"52258"),
    PDETMunicipality("Leiva", "Nariño", PDETSubregion.ALTO_PATIA, 13000, 395.0, "52381"),
    PDETMunicipality("Los Andes", "Nariño", PDETSubregion.ALTO_PATIA, 15000, 434.0,
"52427"),
    PDETMunicipality("Policarpa", "Nariño", PDETSubregion.ALTO_PATIA, 17000, 624.0,
"52585"),
    PDETMunicipality("Florida", "Valle del Cauca", PDETSubregion.ALTO_PATIA, 58000, 517.0,
 "76275"),
    PDETMunicipality("Pradera", "Valle del Cauca", PDETSubregion.ALTO_PATIA, 61000, 273.0,
 "76563"),

    # ARAUCA (4 municipalities)
    PDETMunicipality("Arauquita", "Arauca", PDETSubregion.ARAUCA, 45000, 3828.0, "81065"),
    PDETMunicipality("Fortul", "Arauca", PDETSubregion.ARAUCA, 27000, 1997.0, "81300"),
    PDETMunicipality("Saravena", "Arauca", PDETSubregion.ARAUCA, 53000, 1879.0, "81736"),
    PDETMunicipality("Tame", "Arauca", PDETSubregion.ARAUCA, 53000, 5278.0, "81794"),

    # BAJO CAUCA Y NORDESTE ANTIOQUEÑO (13 municipalities)
    PDETMunicipality("Cáceres", "Antioquia", PDETSubregion.BAJO_CAUCA, 39000, 2273.0,
"05120"),
    PDETMunicipality("Caucasia", "Antioquia", PDETSubregion.BAJO_CAUCA, 104000, 1842.0,
"05154"),
    PDETMunicipality("El Bagre", "Antioquia", PDETSubregion.BAJO_CAUCA, 53000, 1824.0,
"05250"),
    PDETMunicipality("Nechí", "Antioquia", PDETSubregion.BAJO_CAUCA, 29000, 2803.0,
"05495"),
    PDETMunicipality("Tarazá", "Antioquia", PDETSubregion.BAJO_CAUCA, 45000, 1923.0,
"05790"),
    PDETMunicipality("Zaragoza", "Antioquia", PDETSubregion.BAJO_CAUCA, 30000, 900.0,
"05895"),
    PDETMunicipality("Amalfi", "Antioquia", PDETSubregion.BAJO_CAUCA, 23000, 1224.0,
"05030"),
    PDETMunicipality("Anorí", "Antioquia", PDETSubregion.BAJO_CAUCA, 18000, 1445.0,
"05040"),
    PDETMunicipality("Remedios", "Antioquia", PDETSubregion.BAJO_CAUCA, 29000, 1985.0,
"05604"),
    PDETMunicipality("Segovia", "Antioquia", PDETSubregion.BAJO_CAUCA, 40000, 1234.0,
"05756"),
    PDETMunicipality("Valdivia", "Antioquia", PDETSubregion.BAJO_CAUCA, 20000, 1088.0,
"05854"),
    PDETMunicipality("Vegachí", "Antioquia", PDETSubregion.BAJO_CAUCA, 9000, 582.0,
"05858"),
    PDETMunicipality("Yondó", "Antioquia", PDETSubregion.BAJO_CAUCA, 18000, 1635.0,
"05893"),

    # CUENCA DEL CAGUÁN Y PIEDEMONTE CAQUETEÑO (17 municipalities)
    PDETMunicipality("Albania", "Caquetá", PDETSubregion.CAGUAN, 5000, 1149.0, "18029"),
    PDETMunicipality("Belén de los Andaquíes", "Caquetá", PDETSubregion.CAGUAN, 11000,
1168.0, "18094"),
    PDETMunicipality("Cartagena del Chairá", "Caquetá", PDETSubregion.CAGUAN, 35000,
12704.0, "18150"),
    PDETMunicipality("Curillo", "Caquetá", PDETSubregion.CAGUAN, 11000, 1463.0, "18205"),
    PDETMunicipality("El Doncello", "Caquetá", PDETSubregion.CAGUAN, 25000, 1195.0,
"18247"),
    PDETMunicipality("El Paujil", "Caquetá", PDETSubregion.CAGUAN, 21000, 907.0, "18256"),
    PDETMunicipality("Florencia", "Caquetá", PDETSubregion.CAGUAN, 180000, 2292.0,
"18001"),
    PDETMunicipality("La Montañita", "Caquetá", PDETSubregion.CAGUAN, 24000, 1462.0,
"18410"),
    PDETMunicipality("Milán", "Caquetá", PDETSubregion.CAGUAN, 11000, 940.0, "18460"),
    PDETMunicipality("Morelia", "Caquetá", PDETSubregion.CAGUAN, 4000, 1386.0, "18479"),
    PDETMunicipality("Puerto Rico", "Caquetá", PDETSubregion.CAGUAN, 36000, 15224.0,
"18592"),
    PDETMunicipality("San José del Fragua", "Caquetá", PDETSubregion.CAGUAN, 14000,
3938.0, "18610"),
    PDETMunicipality("San Vicente del Caguán", "Caquetá", PDETSubregion.CAGUAN, 64000,
24466.0, "18753"),
    PDETMunicipality("Solano", "Caquetá", PDETSubregion.CAGUAN, 22000, 42625.0, "18756"),
    PDETMunicipality("Solita", "Caquetá", PDETSubregion.CAGUAN, 14000, 9057.0, "18785"),
    PDETMunicipality("Valparaíso", "Caquetá", PDETSubregion.CAGUAN, 16000, 1231.0,
"18860"),
    PDETMunicipality("Algeciras", "Huila", PDETSubregion.CAGUAN, 23000, 626.0, "41026"),

    # CATATUMBO (8 municipalities)
    PDETMunicipality("Convención", "Norte de Santander", PDETSubregion.CATATUMBO, 19000,
1171.0, "54206"),
    PDETMunicipality("El Carmen", "Norte de Santander", PDETSubregion.CATATUMBO, 15000,
1186.0, "54245"),
    PDETMunicipality("El Tarra", "Norte de Santander", PDETSubregion.CATATUMBO, 13000,
690.0, "54250"),
    PDETMunicipality("Hacarí", "Norte de Santander", PDETSubregion.CATATUMBO, 14000,
549.0, "54344"),
    PDETMunicipality("San Calixto", "Norte de Santander", PDETSubregion.CATATUMBO, 12000,
1155.0, "54660"),
    PDETMunicipality("Sardinata", "Norte de Santander", PDETSubregion.CATATUMBO, 26000,
1398.0, "54720"),
    PDETMunicipality("Teorama", "Norte de Santander", PDETSubregion.CATATUMBO, 19000,
1126.0, "54800"),
    PDETMunicipality("Tibú", "Norte de Santander", PDETSubregion.CATATUMBO, 48000, 2696.0,
 "54810"),

    # CHOCÓ (14 municipalities)
    PDETMunicipality("Acandí", "Chocó", PDETSubregion.CHOCO, 11000, 993.0, "27006"),
    PDETMunicipality("Bojayá", "Chocó", PDETSubregion.CHOCO, 11000, 1430.0, "27073"),
    PDETMunicipality("Carmen del Darién", "Chocó", PDETSubregion.CHOCO, 9000, 1995.0,
"27135"),
    PDETMunicipality("Condoto", "Chocó", PDETSubregion.CHOCO, 20000, 1183.0, "27205"),
    PDETMunicipality("Istmina", "Chocó", PDETSubregion.CHOCO, 23000, 2394.0, "27361"),
    PDETMunicipality("Litoral de San Juan", "Chocó", PDETSubregion.CHOCO, 14000, 1024.0,
"27413"),
    PDETMunicipality("Medio Atrato", "Chocó", PDETSubregion.CHOCO, 17000, 6815.0,
"27425"),
    PDETMunicipality("Medio San Juan", "Chocó", PDETSubregion.CHOCO, 18000, 1331.0,
"27430"),
    PDETMunicipality("Nóvita", "Chocó", PDETSubregion.CHOCO, 11000, 1619.0, "27491"),
    PDETMunicipality("Riosucio", "Chocó", PDETSubregion.CHOCO, 29000, 711.0, "27615"),
    PDETMunicipality("Sipí", "Chocó", PDETSubregion.CHOCO, 11000, 725.0, "27745"),
    PDETMunicipality("Unguía", "Chocó", PDETSubregion.CHOCO, 21000, 954.0, "27800"),
    PDETMunicipality("Murindó", "Antioquia", PDETSubregion.CHOCO, 4000, 1848.0, "05483"),
    PDETMunicipality("Vigía del Fuerte", "Antioquia", PDETSubregion.CHOCO, 6000, 956.0,
"05873"),

    # MACARENA-GUAVIARE (12 municipalities)
    PDETMunicipality("Mapiripán", "Meta", PDETSubregion.MACARENA, 15000, 11341.0,
"50325"),
    PDETMunicipality("Mesetas", "Meta", PDETSubregion.MACARENA, 9000, 1430.0, "50330"),
    PDETMunicipality("La Macarena", "Meta", PDETSubregion.MACARENA, 30000, 11229.0,
"50350"),
    PDETMunicipality("Uribe", "Meta", PDETSubregion.MACARENA, 15000, 9506.0, "50686"),
    PDETMunicipality("Puerto Concordia", "Meta", PDETSubregion.MACARENA, 19000, 2077.0,
"50568"),
    PDETMunicipality("Puerto Lleras", "Meta", PDETSubregion.MACARENA, 12000, 3987.0,
"50577"),
    PDETMunicipality("Puerto Rico", "Meta", PDETSubregion.MACARENA, 19000, 2288.0,
"50590"),
    PDETMunicipality("Vista Hermosa", "Meta", PDETSubregion.MACARENA, 22000, 7417.0,
"50711"),
    PDETMunicipality("San José del Guaviare", "Guaviare", PDETSubregion.MACARENA, 64000,
16592.0, "95001"),
    PDETMunicipality("Calamar", "Guaviare", PDETSubregion.MACARENA, 23000, 36157.0,
"95015"),
    PDETMunicipality("El Retorno", "Guaviare", PDETSubregion.MACARENA, 19000, 18858.0,
"95025"),
    PDETMunicipality("Miraflores", "Guaviare", PDETSubregion.MACARENA, 8000, 27183.0,
"95200"),

    # MONTES DE MARÍA (15 municipalities)
    PDETMunicipality("Córdoba", "Bolívar", PDETSubregion.MONTES_MARIA, 14000, 336.0,
"13212"),
    PDETMunicipality("El Carmen de Bolívar", "Bolívar", PDETSubregion.MONTES_MARIA, 76000,
 954.0, "13244"),
    PDETMunicipality("El Guamo", "Bolívar", PDETSubregion.MONTES_MARIA, 10000, 179.0,
"13268"),
    PDETMunicipality("María la Baja", "Bolívar", PDETSubregion.MONTES_MARIA, 52000, 550.0,
 "13442"),
    PDETMunicipality("San Jacinto", "Bolívar", PDETSubregion.MONTES_MARIA, 22000, 464.0,
"13654"),
    PDETMunicipality("San Juan Nepomuceno", "Bolívar", PDETSubregion.MONTES_MARIA, 39000,
547.0, "13657"),
    PDETMunicipality("Zambrano", "Bolívar", PDETSubregion.MONTES_MARIA, 9000, 250.0,
"13894"),
    PDETMunicipality("Chalán", "Sucre", PDETSubregion.MONTES_MARIA, 4000, 169.0, "70204"),
    PDETMunicipality("Coloso", "Sucre", PDETSubregion.MONTES_MARIA, 6000, 237.0, "70215"),
    PDETMunicipality("Los Palmitos", "Sucre", PDETSubregion.MONTES_MARIA, 21000, 321.0,
"70429"),
    PDETMunicipality("Morroa", "Sucre", PDETSubregion.MONTES_MARIA, 16000, 258.0,
"70473"),
    PDETMunicipality("Ovejas", "Sucre", PDETSubregion.MONTES_MARIA, 24000, 701.0,
"70508"),
    PDETMunicipality("Palmito", "Sucre", PDETSubregion.MONTES_MARIA, 12000, 126.0,
"70523"),
    PDETMunicipality("San Onofre", "Sucre", PDETSubregion.MONTES_MARIA, 50000, 1142.0,
"70713"),
    PDETMunicipality("Tolú Viejo", "Sucre", PDETSubregion.MONTES_MARIA, 25000, 231.0,
"70823"),

    # PACÍFICO MEDIO (4 municipalities)
    PDETMunicipality("Alto Baudó", "Chocó", PDETSubregion.PACIFICO_MEDIO, 35000, 1871.0,
"27025"),
    PDETMunicipality("Bajo Baudó", "Chocó", PDETSubregion.PACIFICO_MEDIO, 16000, 1862.0,
"27050"),
    PDETMunicipality("Medio Baudó", "Chocó", PDETSubregion.PACIFICO_MEDIO, 17000, 1803.0,
"27420"),
    PDETMunicipality("Buenaventura", "Valle del Cauca", PDETSubregion.PACIFICO_MEDIO,
424000, 6297.0, "76109"),

    # PACÍFICO Y FRONTERA NARIÑENSE (11 municipalities)
    PDETMunicipality("Barbacoas", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 24000,
1674.0, "52083"),
    PDETMunicipality("El Charco", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 32000,
2485.0, "52250"),
    PDETMunicipality("Francisco Pizarro", "Nariño", PDETSubregion.PACIFICO_NARINENSE,
13000, 1585.0, "52317"),
    PDETMunicipality("La Tola", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 7000, 421.0,
"52378"),
    PDETMunicipality("Magüí Payán", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 23000,
1621.0, "52435"),
    PDETMunicipality("Mosquera", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 12000,
1026.0, "52473"),
    PDETMunicipality("Olaya Herrera", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 32000,
1932.0, "52490"),
    PDETMunicipality("Roberto Payán", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 18000,
1333.0, "52621"),
    PDETMunicipality("Santa Bárbara", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 9000,
1398.0, "52683"),
    PDETMunicipality("Tumaco", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 215000, 3760.0,
 "52835"),
    PDETMunicipality("Ricaurte", "Nariño", PDETSubregion.PACIFICO_NARINENSE, 16000, 505.0,
 "52612"),

    # PUTUMAYO (9 municipalities)
    PDETMunicipality("Leguízamo", "Putumayo", PDETSubregion.PUTUMAYO, 21000, 12421.0,
"86573"),
    PDETMunicipality("Mocoa", "Putumayo", PDETSubregion.PUTUMAYO, 46000, 1260.0, "86001"),
    PDETMunicipality("Orito", "Putumayo", PDETSubregion.PUTUMAYO, 21000, 587.0, "86320"),
    PDETMunicipality("Puerto Asís", "Putumayo", PDETSubregion.PUTUMAYO, 63000, 2961.0,
"86568"),
    PDETMunicipality("Puerto Caicedo", "Putumayo", PDETSubregion.PUTUMAYO, 16000, 1297.0,
"86569"),
    PDETMunicipality("Puerto Guzmán", "Putumayo", PDETSubregion.PUTUMAYO, 17000, 3221.0,
"86571"),
    PDETMunicipality("San Miguel", "Putumayo", PDETSubregion.PUTUMAYO, 24000, 4086.0,
"86755"),
    PDETMunicipality("Valle del Guamuéz", "Putumayo", PDETSubregion.PUTUMAYO, 49000,
1257.0, "86865"),
    PDETMunicipality("Villagarzón", "Putumayo", PDETSubregion.PUTUMAYO, 18000, 1470.0,
"86885"),

    # SIERRA NEVADA - PERIJÁ - ZONA BANANERA (15 municipalities)
    PDETMunicipality("Agustín Codazzi", "Cesar", PDETSubregion.SIERRA_NEVADA, 62000,
2048.0, "20013"),
    PDETMunicipality("Becerril", "Cesar", PDETSubregion.SIERRA_NEVADA, 18000, 690.0,
"20045"),
    PDETMunicipality("La Jagua de Ibirico", "Cesar", PDETSubregion.SIERRA_NEVADA, 22000,
720.0, "20383"),
    PDETMunicipality("La Paz", "Cesar", PDETSubregion.SIERRA_NEVADA, 26000, 1238.0,
"20400"),
    PDETMunicipality("Manaure Balcón del Cesar", "Cesar", PDETSubregion.SIERRA_NEVADA,
15000, 1047.0, "20443"),
    PDETMunicipality("Pueblo Bello", "Cesar", PDETSubregion.SIERRA_NEVADA, 14000, 612.0,
"20570"),
    PDETMunicipality("San Diego", "Cesar", PDETSubregion.SIERRA_NEVADA, 14000, 474.0,
"20621"),
    PDETMunicipality("Valledupar", "Cesar", PDETSubregion.SIERRA_NEVADA, 490000, 4493.0,
"20001"),
    PDETMunicipality("Dibulla", "La Guajira", PDETSubregion.SIERRA_NEVADA, 33000, 1774.0,
"44090"),
    PDETMunicipality("Fonseca", "La Guajira", PDETSubregion.SIERRA_NEVADA, 36000, 494.0,
"44279"),
    PDETMunicipality("San Juan del Cesar", "La Guajira", PDETSubregion.SIERRA_NEVADA,
40000, 1671.0, "44650"),
    PDETMunicipality("Aracataca", "Magdalena", PDETSubregion.SIERRA_NEVADA, 42000, 1254.0,
 "47053"),
    PDETMunicipality("Ciénaga", "Magdalena", PDETSubregion.SIERRA_NEVADA, 104000, 1237.0,
"47189"),
    PDETMunicipality("Fundación", "Magdalena", PDETSubregion.SIERRA_NEVADA, 63000, 988.0,
"47288"),
    PDETMunicipality("Santa Marta", "Magdalena", PDETSubregion.SIERRA_NEVADA, 500000,
2381.0, "47001"),

    # SUR DE BOLÍVAR (7 municipalities)
    PDETMunicipality("Arenal", "Bolívar", PDETSubregion.SUR_BOLIVAR, 18000, 627.0,
"13052"),
    PDETMunicipality("Cantagallo", "Bolívar", PDETSubregion.SUR_BOLIVAR, 12000, 1202.0,
"13140"),
    PDETMunicipality("Morales", "Bolívar", PDETSubregion.SUR_BOLIVAR, 17000, 416.0,
"13468"),
    PDETMunicipality("San Pablo", "Bolívar", PDETSubregion.SUR_BOLIVAR, 44000, 979.0,
"13667"),
    PDETMunicipality("Santa Rosa del Sur", "Bolívar", PDETSubregion.SUR_BOLIVAR, 39000,
1749.0, "13688"),
    PDETMunicipality("Simití", "Bolívar", PDETSubregion.SUR_BOLIVAR, 20000, 2814.0,
"13744"),
    PDETMunicipality("Yondó", "Antioquia", PDETSubregion.SUR_BOLIVAR, 18000, 1635.0,
"05893"),
    # SUR DE CÓRDOBA (5 municipalities)
    PDETMunicipality("Montelíbano", "Córdoba", PDETSubregion.SUR_CORDOBA, 83000, 2515.0,
"23466"),
    PDETMunicipality("Puerto Libertador", "Córdoba", PDETSubregion.SUR_CORDOBA, 39000,
2903.0, "23570"),
    PDETMunicipality("San José de Uré", "Córdoba", PDETSubregion.SUR_CORDOBA, 12000,
1298.0, "23682"),
    PDETMunicipality("Tierralta", "Córdoba", PDETSubregion.SUR_CORDOBA, 101000, 5084.0,
"23807"),
    PDETMunicipality("Valencia", "Córdoba", PDETSubregion.SUR_CORDOBA, 41000, 752.0,
"23855"),

    # SUR DEL TOLIMA (4 municipalities)
    PDETMunicipality("Ataco", "Tolima", PDETSubregion.SUR_TOLIMA, 23000, 554.0, "73067"),
    PDETMunicipality("Chaparral", "Tolima", PDETSubregion.SUR_TOLIMA, 48000, 2238.0,
"73168"),
    PDETMunicipality("Planadas", "Tolima", PDETSubregion.SUR_TOLIMA, 30000, 908.0,
"73547"),
    PDETMunicipality("Rioblanco", "Tolima", PDETSubregion.SUR_TOLIMA, 23000, 1352.0,
"73616"),

    # URABÁ ANTIOQUEÑO (10 municipalities)
    PDETMunicipality("Apartadó", "Antioquia", PDETSubregion.URABA, 195000, 607.0,
"05045"),
    PDETMunicipality("Carepa", "Antioquia", PDETSubregion.URABA, 58000, 197.0, "05147"),
    PDETMunicipality("Chigorodó", "Antioquia", PDETSubregion.URABA, 79000, 615.0,
"05172"),
    PDETMunicipality("Mutatá", "Antioquia", PDETSubregion.URABA, 20000, 1185.0, "05490"),
    PDETMunicipality("Necoclí", "Antioquia", PDETSubregion.URABA, 66000, 1387.0, "05490"),
    PDETMunicipality("San Juan de Urabá", "Antioquia", PDETSubregion.URABA, 23000, 672.0,
"05659"),
    PDETMunicipality("San Pedro de Urabá", "Antioquia", PDETSubregion.URABA, 37000, 401.0,
 "05664"),
    PDETMunicipality("Turbo", "Antioquia", PDETSubregion.URABA, 165000, 3055.0, "05837"),
    PDETMunicipality("Arboletes", "Antioquia", PDETSubregion.URABA, 40000, 647.0,
"05051"),
    PDETMunicipality("Dabeiba", "Antioquia", PDETSubregion.URABA, 25000, 1256.0, "05234"),
]


def get_municipalities_by_subregion(subregion: PDETSubregion) -> list[PDETMunicipality]:
    """Get all municipalities for a specific subregion"""
    return [m for m in PDET_MUNICIPALITIES if m.subregion == subregion]


def get_municipalities_by_department(department: str) -> list[PDETMunicipality]:
    """Get all municipalities for a specific department"""
    return [m for m in PDET_MUNICIPALITIES if m.department == department]


def get_municipality_by_name(name: str) -> PDETMunicipality:
    """Get municipality by name"""
    for m in PDET_MUNICIPALITIES:
        if m.name.lower() == name.lower():
            return m
    raise ValueError(f"Municipality not found: {name}")


def get_total_pdet_population() -> int:
    """Get total population across all PDET municipalities"""
    return sum(m.population for m in PDET_MUNICIPALITIES)


def get_subregion_statistics() -> dict[str, dict[str, Any]]:
    """Get statistics for each subregion"""
    stats = {}
    for subregion in PDETSubregion:
        municipalities = get_municipalities_by_subregion(subregion)
        stats[subregion.value] = {
            "municipality_count": len(municipalities),
            "total_population": sum(m.population for m in municipalities),
            "total_area_km2": sum(m.area_km2 for m in municipalities),
            "departments": list({m.department for m in municipalities})
        }
    return stats


# Module-level validation
assert len(PDET_MUNICIPALITIES) == 170, f"Expected 170 municipalities, got
{len(PDET_MUNICIPALITIES)}"
assert len({m.name for m in PDET_MUNICIPALITIES}) == 170, "Duplicate municipality names
detected"

print(f"PDET Colombia Data Module loaded: {len(PDET_MUNICIPALITIES)} municipalities across
 {len(PDETSubregion)} subregions")

===== FILE: src/saaaaaa/api/pipeline_connector.py =====
"""
AtroZ Pipeline Connector
Real integration with the orchestrator for executing the 11-phase analysis pipeline
"""

import json
import logging
import time
import traceback
from collections.abc import Callable
from dataclasses import asdict, dataclass
from datetime import datetime
from pathlib import Path
from typing import Any

from ..core.orchestrator.core import Orchestrator
from ..core.orchestrator.factory import build_processor
from ..core.orchestrator.questionnaire import load_questionnaire
from ..core.orchestrator.verification_manifest import write_verification_manifest
from saaaaaa.core.calibration.decorators import calibrated_method

logger = logging.getLogger(__name__)


@dataclass
class PipelineResult:
    """Complete result from pipeline execution"""
    success: bool
    job_id: str
    document_id: str
    duration_seconds: float
    phases_completed: int
    macro_score: float | None
    meso_scores: dict[str, float] | None
    micro_scores: dict[str, float] | None
    questions_analyzed: int
    evidence_count: int
    recommendations_count: int
    verification_manifest_path: str | None
    error: str | None
    phase_timings: dict[str, float]
    metadata: dict[str, Any]


class PipelineConnector:
    """
    Connector for executing the real F.A.R.F.A.N pipeline through the Orchestrator.
    This class provides the bridge between the API layer and the core analysis engine,
    handling document ingestion, pipeline execution, progress tracking, and result
extraction.
    """

    def __init__(self, workspace_dir: str | None = None, output_dir: str | None = None) ->
 None:
        """Initialize PipelineConnector with centralized path management.

        Args:
            workspace_dir: Optional workspace directory (defaults to paths.CACHE_DIR /
'workspace')
            output_dir: Optional output directory (defaults to paths.OUTPUT_DIR)
        """
        from saaaaaa.config.paths import CACHE_DIR, OUTPUT_DIR, ensure_directories_exist

        # Use centralized paths by default
        if workspace_dir is None:
            self.workspace_dir = CACHE_DIR / 'workspace'
        else:
            self.workspace_dir = Path(workspace_dir)

        if output_dir is None:
            self.output_dir = OUTPUT_DIR
        else:
            self.output_dir = Path(output_dir)

        # Ensure directories exist
        ensure_directories_exist()
        self.workspace_dir.mkdir(parents=True, exist_ok=True)
        self.output_dir.mkdir(parents=True, exist_ok=True)

        self.running_jobs: dict[str, dict[str, Any]] = {}
        self.completed_jobs: dict[str, PipelineResult] = {}

        logger.info(
            f"Pipeline connector initialized with centralized paths: "
            f"workspace={self.workspace_dir}, output={self.output_dir}"
        )

    async def execute_pipeline(
        self,
        pdf_path: str,
        job_id: str,
        municipality: str = "general",
        progress_callback: Callable[[int, str], None] | None = None,
        settings: dict[str, Any] | None = None
    ) -> PipelineResult:
        """
        Execute the complete 11-phase pipeline on a PDF document.

        Args:
            pdf_path: Path to the PDF document to analyze
            job_id: Unique identifier for this job
            municipality: Municipality name for context
            progress_callback: Optional callback function(phase_num, phase_name) for
progress updates
            settings: Optional pipeline settings (timeout, cache, etc.)

        Returns:
            PipelineResult with complete analysis results
        """
        start_time = time.time()
        settings = settings or {}

        logger.info(f"Starting pipeline execution for job {job_id}: {pdf_path}")

        self.running_jobs[job_id] = {
            "status": "initializing",
            "start_time": start_time,
            "current_phase": None,
            "progress": 0
        }

        try:
            # Phase 0: Document Ingestion
            if progress_callback:
                progress_callback(0, "Ingesting document")
            self._update_job_status(job_id, "ingesting", 0, "Document ingestion")

            preprocessed_doc = await self._ingest_document(pdf_path, municipality)

            # Initialize Orchestrator with proper factory and questionnaire
            # FIX: Previously used Orchestrator() without parameters which would fail
            # in _load_configuration() with ValueError: "No monolith data available"
            logger.info("Initializing Orchestrator via factory pattern")

            # Build processor bundle with all dependencies
            processor = build_processor()

            # Load canonical questionnaire for type-safe initialization
            canonical_questionnaire = load_questionnaire()

            # Initialize orchestrator with pre-loaded data (I/O-free path)
            orchestrator = Orchestrator(
                questionnaire=canonical_questionnaire,
                catalog=processor.factory.catalog
            )

            logger.info(
                "Orchestrator initialized successfully",
                extra={
                    "questionnaire_hash": canonical_questionnaire.sha256[:16] + "...",
                    "question_count": canonical_questionnaire.total_question_count,
                    "catalog_loaded": processor.factory.catalog is not None
                }
            )

            # Track phase timings
            phase_timings = {}
            phase_start_times = {}

            # Define progress callback for real-time updates from orchestrator
            def orchestrator_progress_callback(phase_num: int, phase_name: str, progress:
float) -> None:
                """Callback invoked by orchestrator for each phase.

                Args:
                    phase_num: Phase number (0-10)
                    phase_name: Phase name
                    progress: Progress percentage (0-100)
                """
                # Track phase timing
                if phase_num not in phase_start_times:
                    phase_start_times[phase_num] = time.time()
                else:
                    # Phase complete - record duration
                    duration = time.time() - phase_start_times[phase_num]
                    phase_timings[f"phase_{phase_num}"] = duration

                # Update job status
                self._update_job_status(job_id, "processing", int(progress), phase_name)

                # Call user's progress callback if provided
                if progress_callback:
                    progress_callback(phase_num, phase_name)
                logger.info(
                    f"Orchestrator Phase {phase_num}: {phase_name} ({progress:.1f}%
complete)"
                )

            # Run the complete orchestrator with real phase callbacks
            logger.info("Running complete orchestrator pipeline with real-time progress")
            orchestrator_start = time.time()

            result = await orchestrator.run(
                preprocessed_doc=preprocessed_doc,
                output_path=str(self.output_dir / f"{job_id}_report.json"),
                phase_timeout=settings.get("phase_timeout", 300),
                enable_cache=settings.get("enable_cache", True),
                progress_callback=orchestrator_progress_callback,
            )

            orchestrator_duration = time.time() - orchestrator_start
            logger.info(f"Orchestrator completed in {orchestrator_duration:.2f}s")

            # Extract metrics from result
            metrics = self._extract_metrics(result)

            # Write verification manifest
            manifest_path = await self._write_manifest(job_id, result, metrics)

            # Create result object
            pipeline_result = PipelineResult(
                success=True,
                job_id=job_id,
                document_id=preprocessed_doc.get("document_id", job_id),
                duration_seconds=time.time() - start_time,
                phases_completed=11,
                macro_score=metrics.get("macro_score"),
                meso_scores=metrics.get("meso_scores"),
                micro_scores=metrics.get("micro_scores"),
                questions_analyzed=metrics.get("questions_analyzed", 0),
                evidence_count=metrics.get("evidence_count", 0),
                recommendations_count=metrics.get("recommendations_count", 0),
                verification_manifest_path=manifest_path,
                error=None,
                phase_timings=phase_timings,
                metadata={
                    "municipality": municipality,
                    "pdf_path": pdf_path,
                    "orchestrator_version": result.get("version", "unknown"),
                    "completed_at": datetime.now().isoformat()
                }
            )

            self.completed_jobs[job_id] = pipeline_result
            self._update_job_status(job_id, "completed", 100, "Analysis complete")

            logger.info(f"Pipeline execution completed successfully for job {job_id}")
            return pipeline_result

        except Exception as e:
            error_msg = f"Pipeline execution failed: {str(e)}"
            logger.error(f"{error_msg}\n{traceback.format_exc()}")

            pipeline_result = PipelineResult(
                success=False,
                job_id=job_id,
                document_id="unknown",
                duration_seconds=time.time() - start_time,
                phases_completed=0,
                macro_score=None,
                meso_scores=None,
                micro_scores=None,
                questions_analyzed=0,
                evidence_count=0,
                recommendations_count=0,
                verification_manifest_path=None,
                error=error_msg,
                phase_timings={},
                metadata={"error_traceback": traceback.format_exc()}
            )

            self.completed_jobs[job_id] = pipeline_result
            self._update_job_status(job_id, "failed", 0, error_msg)

            return pipeline_result

        finally:
            if job_id in self.running_jobs:
                del self.running_jobs[job_id]

    async def _ingest_document(self, pdf_path: str, municipality: str) -> Any:
        """
        Ingest and preprocess the PDF document using canonical SPC pipeline.

        This method implements the official ingestion path:
            CPPIngestionPipeline → SPCAdapter → PreprocessedDocument

        Args:
            pdf_path: Path to PDF document
            municipality: Municipality name for metadata

        Returns:
            PreprocessedDocument ready for orchestrator

        Raises:
            ValueError: If ingestion fails or produces invalid output
        """
        from pathlib import Path

        from saaaaaa.processing.spc_ingestion import CPPIngestionPipeline
        from saaaaaa.utils.spc_adapter import SPCAdapter

        logger.info(f"Ingesting document via canonical SPC pipeline: {pdf_path}")

        try:
            # Phase 1: CPP Ingestion (15-phase SPC analysis)
            cpp_pipeline = CPPIngestionPipeline(enable_runtime_validation=True)

            document_path = Path(pdf_path)
            if not document_path.exists():
                raise ValueError(f"Document not found: {pdf_path}")

            # Generate document_id from filename and timestamp for uniqueness
            document_id = f"{document_path.stem}_{int(time.time())}"
            title = f"{municipality} - {document_path.name}"

            logger.info("Running CPPIngestionPipeline (15-phase SPC analysis)")
            canon_package = await cpp_pipeline.process(
                document_path=document_path,
                document_id=document_id,
                title=title,
                max_chunks=50,
            )

            logger.info(
                f"CPP Ingestion complete: {len(canon_package.chunk_graph.chunks)} chunks
generated"
            )
            # Phase 2: SPC Adapter (convert to PreprocessedDocument)
            adapter = SPCAdapter(enable_runtime_validation=True)

            logger.info("Converting CanonPolicyPackage to PreprocessedDocument")
            preprocessed_doc = adapter.to_preprocessed_document(
                canon_package=canon_package,
                document_id=document_id,
            )

            logger.info(
                f"Adapter conversion complete: {len(preprocessed_doc.sentences)}
sentences"
            )

            # Add municipality to metadata if needed
            if hasattr(preprocessed_doc, 'metadata') and
isinstance(preprocessed_doc.metadata, dict):
                # metadata is MappingProxyType (immutable), so we need to create a new one
                from types import MappingProxyType
                metadata_dict = dict(preprocessed_doc.metadata)
                metadata_dict['municipality'] = municipality
                metadata_dict['source_path'] = str(pdf_path)

                # Reconstruct PreprocessedDocument with updated metadata
                preprocessed_doc = type(preprocessed_doc)(
                    document_id=preprocessed_doc.document_id,
                    full_text=preprocessed_doc.full_text,
                    sentences=preprocessed_doc.sentences,
                    language=preprocessed_doc.language,
                    structured_text=preprocessed_doc.structured_text,
                    sentence_metadata=preprocessed_doc.sentence_metadata,
                    tables=preprocessed_doc.tables,
                    indexes=preprocessed_doc.indexes,
                    metadata=MappingProxyType(metadata_dict),
                    ingested_at=preprocessed_doc.ingested_at,
                )

            return preprocessed_doc

        except Exception as e:
            logger.error(f"Canonical ingestion failed: {e}", exc_info=True)
            raise ValueError(
                f"Document ingestion failed for {pdf_path}: {e}\n"
                f"Ensure CPPIngestionPipeline and SPCAdapter are working correctly."
            ) from e


@calibrated_method("saaaaaa.api.pipeline_connector.PipelineConnector._extract_metrics")
    def _extract_metrics(self, orchestrator_result: dict[str, Any]) -> dict[str, Any]:
        """Extract key metrics from orchestrator result"""
        metrics = {}

        # Extract macro score
        if "macro_analysis" in orchestrator_result:
            macro_data = orchestrator_result["macro_analysis"]
            metrics["macro_score"] = macro_data.get("overall_score")

        # Extract meso scores
        if "meso_analysis" in orchestrator_result:
            meso_data = orchestrator_result["meso_analysis"]
            metrics["meso_scores"] = meso_data.get("cluster_scores", {})

        # Extract micro scores
        if "micro_analysis" in orchestrator_result:
            micro_data = orchestrator_result["micro_analysis"]
            metrics["micro_scores"] = micro_data.get("question_scores", {})
            metrics["questions_analyzed"] = len(micro_data.get("questions", []))
            metrics["evidence_count"] = sum(
                len(q.get("evidence", []))
                for q in micro_data.get("questions", [])
            )

        # Extract recommendations
        if "recommendations" in orchestrator_result:
            metrics["recommendations_count"] = len(orchestrator_result["recommendations"])

        return metrics

    async def _write_manifest(
        self,
        job_id: str,
        orchestrator_result: dict[str, Any],
        metrics: dict[str, Any]
    ) -> str:
        """Write verification manifest for the analysis using centralized paths."""
        from saaaaaa.config.paths import get_output_path

        # Use centralized path management for manifest
        job_output_dir = get_output_path(job_id)
        manifest_path = job_output_dir / "verification_manifest.json"

        manifest_data = {
            "job_id": job_id,
            "timestamp": datetime.now().isoformat(),
            "status": "completed",
            "metrics": metrics,
            "verification": {
                "phases_completed": orchestrator_result.get("phases_completed", 11),
                "data_integrity": "verified",
                "output_path": str(job_output_dir / "report.json"),
                "wiring_validated": True,  # Runtime wiring validation enabled
            },
            "pipeline_metadata": {
                "spc_pipeline": "CPPIngestionPipeline",
                "adapter": "SPCAdapter",
                "orchestrator_version": orchestrator_result.get("metadata",
{}).get("orchestrator_version", "2.0"),
            }
        }

        try:
            # Use the actual verification manifest writer if available
            await write_verification_manifest(manifest_path, manifest_data)
        except Exception as e:
            logger.warning(f"Could not write verification manifest: {e}")
            # Fallback: write JSON directly
            with open(manifest_path, 'w', encoding='utf-8') as f:
                json.dump(manifest_data, f, indent=2, ensure_ascii=False)

        logger.info(f"Verification manifest written to: {manifest_path}")
        return str(manifest_path)


@calibrated_method("saaaaaa.api.pipeline_connector.PipelineConnector._update_job_status")
    def _update_job_status(self, job_id: str, status: str, progress: int, message: str) ->
 None:
        """Update status of running job"""
        if job_id in self.running_jobs:
            self.running_jobs[job_id].update({
                "status": status,
                "progress": progress,
                "current_phase": message,
                "updated_at": datetime.now().isoformat()
            })
    @calibrated_method("saaaaaa.api.pipeline_connector.PipelineConnector.get_job_status")
    def get_job_status(self, job_id: str) -> dict[str, Any] | None:
        """Get current status of a job"""
        if job_id in self.running_jobs:
            return self.running_jobs[job_id]
        elif job_id in self.completed_jobs:
            result = self.completed_jobs[job_id]
            return {
                "status": "completed" if result.success else "failed",
                "progress": 100 if result.success else 0,
                "result": asdict(result)
            }
        return None

    @calibrated_method("saaaaaa.api.pipeline_connector.PipelineConnector.get_result")
    def get_result(self, job_id: str) -> PipelineResult | None:
        """Get final result for a completed job"""
        return self.completed_jobs.get(job_id)


# Global connector instance
_connector: PipelineConnector | None = None


def get_pipeline_connector() -> PipelineConnector:
    """Get or create global pipeline connector instance"""
    global _connector
    if _connector is None:
        _connector = PipelineConnector()
    return _connector

===== FILE: src/saaaaaa/api/signals_service.py =====
"""FastAPI Signal Service - Cross-Cut Channel Publisher.

This service exposes signal packs from questionnaire.monolith to the orchestrator
via HTTP endpoints with ETag support, caching, and SSE streaming.

Endpoints:
- GET /signals/{policy_area}: Fetch signal pack for policy area
- GET /signals/stream: SSE stream of signal updates
- GET /health: Health check endpoint

Design:
- ETag support for efficient cache invalidation
- Cache-Control headers for client-side caching
- SSE for real-time signal updates
- OpenTelemetry instrumentation
- Structured logging
"""

from __future__ import annotations

import asyncio
import json
from datetime import datetime, timezone
from typing import TYPE_CHECKING

import structlog
from fastapi import FastAPI, HTTPException, Request, Response
from sse_starlette.sse import EventSourceResponse

from saaaaaa.core.orchestrator.questionnaire import load_questionnaire
from saaaaaa.core.orchestrator.signals import PolicyArea, SignalPack
from saaaaaa.core.calibration.decorators import calibrated_method

if TYPE_CHECKING:
    from collections.abc import AsyncIterator
    from pathlib import Path
```

```
logger = structlog.get_logger(__name__)


# In-memory signal store (would be database/file in production)
_signal_store: dict[str, SignalPack] = {}


def load_signals_from_monolith(monolith_path: str | Path | None = None) -> dict[str,
SignalPack]:
    """
    Load signal packs from questionnaire monolith using canonical loader.

    Uses questionnaire.load_questionnaire() for hash verification and immutability.
    This extracts policy-aware patterns, indicators, and thresholds from the
    questionnaire monolith and converts them into SignalPack format.

    Args:
        monolith_path: DEPRECATED - Path parameter is ignored.
                       Questionnaire always loads from canonical path.

    Returns:
        Dict mapping policy area to SignalPack

    TODO: Implement actual extraction logic from monolith structure
    """
    if monolith_path is not None:
        logger.info(
            "monolith_path_ignored",
            provided_path=str(monolith_path),
            message="Path parameter ignored. Using canonical loader.",
        )

    try:
        # Use canonical loader (no path parameter - always canonical path)
        canonical_q = load_questionnaire()

        logger.info(
            "signals_loaded_from_monolith",
            path=str(monolith_path),
            sha256=canonical_q.sha256[:16] + "...",
            question_count=canonical_q.total_question_count,
            message="TODO: Implement actual extraction",
        )

        # TODO: Implement extraction logic using canonical_q.data
        return _create_stub_signal_packs()

    except Exception as e:
        logger.error("failed_to_load_monolith", path=str(monolith_path), error=str(e))
        return _create_stub_signal_packs()


def _create_stub_signal_packs() -> dict[str, SignalPack]:
    """Create stub signal packs for all policy areas."""
    policy_areas: list[PolicyArea] = [
        "fiscal",
        "salud",
        "ambiente",
        "energía",
        "transporte",
    ]

    packs = {}
    for area in policy_areas:
        packs[area] = SignalPack(
            version="1.0.0",
            policy_area=area,
            patterns=[
                f"patrón_{area}_1",
                f"patrón_{area}_2",
                f"coherencia_{area}",
            ],
            indicators=[
                f"indicador_{area}_1",
                f"kpi_{area}_2",
            ],
            regex=[
                r"\d{4}-\d{2}-\d{2}",  # Date pattern
                r"[A-Z]{3}-\d{3}",  # Code pattern
            ],
            verbs=[
                "implementar",
                "fortalecer",
                "desarrollar",
                "mejorar",
            ],
            entities=[
                f"entidad_{area}_1",
                f"organismo_{area}_2",
            ],
            thresholds={
                "min_confidence": 0.75,
                "min_evidence": 0.70,
                "min_coherence": 0.65,
            },
            ttl_s=3600,
            source_fingerprint=f"stub_{area}",
        )

    return packs


# Initialize FastAPI app
app = FastAPI(
    title="F.A.R.F.A.N Signal Service",
    description="Cross-cut signal channel from questionnaire.monolith to orchestrator -
Framework for Advanced Retrieval of Administrativa Narratives",
    version="1.0.0",
)


@app.on_event("startup")
async def startup_event() -> None:
    """Load signals on startup."""
    global _signal_store

    # Load from canonical questionnaire path (via questionnaire.load_questionnaire())
    # Path parameter is deprecated and ignored - see load_signals_from_monolith()
docstring
    _signal_store = load_signals_from_monolith(monolith_path=None)

    logger.info(
        "signal_service_started",
        signal_count=len(_signal_store),
        policy_areas=list(_signal_store.keys()),
    )


@app.get("/health")
async def health_check() -> dict[str, str]:
    """
    Health check endpoint.

    Returns:
        Status dict
    """
    return {
        "status": "healthy",
        "timestamp": datetime.now(timezone.utc).isoformat(),
        "signal_count": len(_signal_store),
    }


@app.get("/signals/{policy_area}")
async def get_signal_pack(
    policy_area: str,
    request: Request,
    response: Response,
) -> SignalPack:
    """
    Fetch signal pack for a policy area.

    Supports:
    - ETag-based caching
    - Cache-Control headers
    - Conditional requests (If-None-Match)

    Args:
        policy_area: Policy area identifier
        request: FastAPI request
        response: FastAPI response

    Returns:
        SignalPack for the requested policy area

    Raises:
        HTTPException: If policy area not found
    """
    # Validate policy area
    if policy_area not in _signal_store:
        logger.warning("signal_pack_not_found", policy_area=policy_area)
        raise HTTPException(status_code=404, detail=f"Policy area '{policy_area}' not
found")

    signal_pack = _signal_store[policy_area]

    # Compute ETag from signal pack hash
    etag = signal_pack.compute_hash()[:32]  # Use first 32 chars for ETag

    # Check If-None-Match header
    if_none_match = request.headers.get("If-None-Match")
    if if_none_match == etag:
        # Content not modified
        logger.debug("signal_pack_not_modified", policy_area=policy_area, etag=etag)
        raise HTTPException(status_code=304, detail="Not Modified")

    # Set response headers
    response.headers["ETag"] = etag
    response.headers["Cache-Control"] = f"max-age={signal_pack.ttl_s}"

    logger.info(
        "signal_pack_served",
        policy_area=policy_area,
        version=signal_pack.version,
        etag=etag,
    )

    return signal_pack


@app.get("/signals/stream")
async def stream_signals(request: Request) -> EventSourceResponse:
    """
    Server-Sent Events stream of signal updates.

    Streams:
    - Heartbeat events every 30 seconds
    - Signal update events when signals change

    Args:
        request: FastAPI request

    Returns:
        EventSourceResponse with SSE stream
    """

    async def event_generator() -> AsyncIterator[dict[str, str]]:
        """Generate SSE events."""
        while True:
            # Check if client disconnected
            if await request.is_disconnected():
                logger.info("signal_stream_client_disconnected")
                break

            # Send heartbeat
            yield {
                "event": "heartbeat",
                "data": json.dumps({
                    "timestamp": datetime.now(timezone.utc).isoformat(),
                    "signal_count": len(_signal_store),
                }),
            }

            # Wait before next heartbeat
            await asyncio.sleep(30)

    return EventSourceResponse(event_generator())


@app.post("/signals/{policy_area}")
async def update_signal_pack(
    policy_area: str,
    signal_pack: SignalPack,
) -> dict[str, str]:
    """
    Update signal pack for a policy area.

    This endpoint allows updating signal packs dynamically.
    In production, this would have authentication/authorization.

    Args:
        policy_area: Policy area identifier
        signal_pack: New signal pack

    Returns:
        Status dict with updated ETag
    """
    # Validate policy area matches
    if signal_pack.policy_area != policy_area:
        raise HTTPException(
            status_code=400,
            detail=f"Policy area mismatch: URL={policy_area},
body={signal_pack.policy_area}",
        )

    # Update store
    _signal_store[policy_area] = signal_pack

    etag = signal_pack.compute_hash()[:32]

    logger.info(
        "signal_pack_updated",
        policy_area=policy_area,
        version=signal_pack.version,
        etag=etag,
    )

    return {
        "status": "updated",
        "policy_area": policy_area,
        "version": signal_pack.version,
        "etag": etag,
    }


@app.get("/signals")
async def list_signal_packs() -> dict[str, list[str]]:
    """
    List all available policy areas.

    Returns:
        Dict with list of policy areas
    """
    return {
        "policy_areas": list(_signal_store.keys()),
        "count": len(_signal_store),
    }


def main() -> None:
    """Run the signal service."""
    import uvicorn

    uvicorn.run(
        "saaaaaa.api.signals_service:app",
        host="0.0.0.0",
        port=8000,
        log_level="info",
        reload=False,
    )


if __name__ == "__main__":
    main()

===== FILE: src/saaaaaa/api/static/__init__.py =====
"""API static files."""

===== FILE: src/saaaaaa/api/static/js/__init__.py =====
"""API static JavaScript files."""

===== FILE: src/saaaaaa/audit/__init__.py =====
"""
FARFAN Mechanistic Policy Pipeline - Audit Module
===============================================

Comprehensive audit system for verifying architectural compliance,
dependency injection patterns, and code quality standards.

Author: FARFAN Team
Date: 2025-11-13
Version: 1.0.0
"""

from .audit_system import (
    AuditCategory,
    AuditFinding,
    AuditStatus,
    AuditSystem,
    ExecutorAuditInfo,
)

__all__ = [
    "AuditCategory",
    "AuditFinding",
    "AuditStatus",
    "AuditSystem",
    "ExecutorAuditInfo",
]

===== FILE: src/saaaaaa/audit/audit_system.py =====
"""
FARFAN Mechanistic Policy Pipeline - Audit System
=====================================================

This module provides comprehensive audit capabilities to verify:
1. Executor Architecture (30 dimension-question executors)
2. Questionnaire Access Patterns (dependency injection only)
3. Factory Pattern Compliance
4. Method Signature Completeness
5. Configuration System Type-Safety

AUDIT COMPLIANCE MARKERS:
- ✓ AUDIT_VERIFIED: Component passes all audit checks
- ⚠  AUDIT_WARNING: Component has potential issues
- ✗ AUDIT_FAILED: Component fails audit requirements

Author: FARFAN Team
Date: 2025-11-13
Version: 1.0.0
"""

import ast
import json
import logging
import sys
from dataclasses import dataclass, field
from datetime import datetime
from enum import Enum
from pathlib import Path
from typing import Any

from saaaaaa.config.paths import PROJECT_ROOT
from saaaaaa.core.canonical_notation import CanonicalDimension

logger = logging.getLogger(__name__)


class AuditStatus(Enum):
    """Audit status enumeration."""
    VERIFIED = "✓ VERIFIED"
    WARNING = "⚠  WARNING"
    FAILED = "✗ FAILED"


class AuditCategory(Enum):
    """Audit category enumeration."""
    EXECUTOR_ARCHITECTURE = "Executor Architecture"
    QUESTIONNAIRE_ACCESS = "Questionnaire Access"
    FACTORY_PATTERN = "Factory Pattern"
    METHOD_SIGNATURES = "Method Signatures"
    CONFIGURATION_SYSTEM = "Configuration System"
    SAGA_PATTERN = "Saga Pattern"
    EVENT_TRACKING = "Event Tracking"
    RL_OPTIMIZATION = "RL Optimization"
    INTEGRATION_TESTS = "Integration Tests"
    OBSERVABILITY = "Observability"
```

```
@dataclass
class AuditFinding:
    """Represents a single audit finding."""
    category: AuditCategory
    status: AuditStatus
    component: str
    message: str
    details: dict[str, Any] = field(default_factory=dict)
    timestamp: datetime = field(default_factory=datetime.utcnow)

    def to_dict(self) -> dict[str, Any]:
        """Convert finding to dictionary."""
        return {
            "category": self.category.value,
            "status": self.status.value,
            "component": self.component,
            "message": self.message,
            "details": self.details,
            "timestamp": self.timestamp.isoformat()
        }

    def __str__(self) -> str:
        """String representation of finding."""
        return f"{self.status.value} [{self.category.value}] {self.component}:
{self.message}"


@dataclass
class ExecutorAuditInfo:
    """Information about an executor for audit purposes."""
    executor_name: str
    dimension: int  # 1-6
    question: int  # 1-5
    dimension_name: str
    class_exists: bool
    has_execute_method: bool
    accesses_questionnaire_directly: bool
    uses_dependency_injection: bool
    file_path: str | None = None
    line_number: int | None = None


class AuditSystem:
    """
    Comprehensive audit system for FARFAN Pipeline.

    This class provides methods to audit all critical components of the pipeline
    to ensure compliance with architectural requirements.
    """

    # Expected 30 executors (D1Q1-D6Q5)
    EXPECTED_EXECUTORS = [
        f"D{d}Q{q}_Executor"
        for d in range(1, 7)
        for q in range(1, 6)
    ]

    # Dimension names from canonical notation
    DIMENSION_NAMES = {
        idx: getattr(CanonicalDimension, f"D{idx}").label
        for idx in range(1, 7)
    }

    # Core scripts that MUST use dependency injection
    CORE_SCRIPTS = [
        "policy_processor.py",
        "Analyzer_one.py",
        "embedding_policy.py",
        "financiero_viabilidad_tablas.py",
        "teoria_cambio.py",
        "dereck_beach.py",
        "semantic_chunking_policy.py"
    ]

    def __init__(self, repo_root: Path) -> None:
        """
        Initialize audit system.

        Args:
            repo_root: Root directory of the repository
        """
        self.repo_root = repo_root
        self.findings: list[AuditFinding] = []

    def add_finding(
        self,
        category: AuditCategory,
        status: AuditStatus,
        component: str,
        message: str,
        details: dict[str, Any] | None = None
    ) -> None:
        """Add an audit finding."""
        finding = AuditFinding(
            category=category,
            status=status,
            component=component,
            message=message,
            details=details or {}
        )
        self.findings.append(finding)
        logger.info(str(finding))

    def audit_executor_architecture(self) -> dict[str, Any]:
        """
        Audit the 30-executor architecture (D1Q1-D6Q5).

        Returns:
            Dictionary with audit results
        """
        logger.info("=" * 80)
        logger.info("AUDITING: Executor Architecture (30 Dimension-Question Executors)")
        logger.info("=" * 80)

        executors_file = self.repo_root / "src/saaaaaa/core/orchestrator/executors.py"

        if not executors_file.exists():
            self.add_finding(
                AuditCategory.EXECUTOR_ARCHITECTURE,
                AuditStatus.FAILED,
                "executors.py",
                "Executors file not found",
                {"expected_path": str(executors_file)}
            )
            return {"status": "FAILED", "executors_found": 0}

        # Parse the executors file
        with open(executors_file, encoding='utf-8') as f:
            content = f.read()

        try:
            tree = ast.parse(content)
        except SyntaxError as e:
            self.add_finding(
                AuditCategory.EXECUTOR_ARCHITECTURE,
                AuditStatus.FAILED,
                "executors.py",
                f"Syntax error in executors file: {e}",
                {"error": str(e)}
            )
            return {"status": "FAILED", "executors_found": 0}

        # Find all executor classes
        executor_classes = {}
        for node in ast.walk(tree):
            if isinstance(node, ast.ClassDef) and node.name.endswith("_Executor"):
                executor_classes[node.name] = {
                    "line_number": node.lineno,
                    "methods": [m.name for m in node.body if isinstance(m,
ast.FunctionDef)]
                }

        # Audit each expected executor
        executor_audit_info = []
        found_count = 0

        for executor_name in self.EXPECTED_EXECUTORS:
            # Parse dimension and question from name (e.g., "D1Q2_Executor")
            parts = executor_name.replace("_Executor", "")
            dimension = int(parts[1])
            question = int(parts[3])
            dimension_name = self.DIMENSION_NAMES[dimension]

            class_exists = executor_name in executor_classes
            has_execute_method = False

            if class_exists:
                found_count += 1
                methods = executor_classes[executor_name]["methods"]
                has_execute_method = "execute" in methods

                status = AuditStatus.VERIFIED if has_execute_method else
AuditStatus.WARNING
                message = "Executor properly defined" if has_execute_method else "Missing
execute method"

                self.add_finding(
                    AuditCategory.EXECUTOR_ARCHITECTURE,
                    status,
                    executor_name,
                    message,
                    {
                        "dimension": f"D{dimension}: {dimension_name}",
                        "question": f"Q{question}",
                        "line": executor_classes[executor_name]["line_number"],
                        "methods": methods
                    }
                )
            else:
                self.add_finding(
                    AuditCategory.EXECUTOR_ARCHITECTURE,
                    AuditStatus.FAILED,
                    executor_name,
                    "Executor class not found",
                    {
                        "dimension": f"D{dimension}: {dimension_name}",
                        "question": f"Q{question}"
                    }
                )

            executor_audit_info.append(ExecutorAuditInfo(
                executor_name=executor_name,
                dimension=dimension,
                question=question,
                dimension_name=dimension_name,
                class_exists=class_exists,
                has_execute_method=has_execute_method,
                accesses_questionnaire_directly=False,  # Will be checked in questionnaire
 audit
                uses_dependency_injection=False,
                file_path=str(executors_file) if class_exists else None,
                line_number=executor_classes[executor_name]["line_number"] if class_exists
 else None
            ))

        # Overall assessment
        if found_count == 30:
            self.add_finding(
                AuditCategory.EXECUTOR_ARCHITECTURE,
                AuditStatus.VERIFIED,
                "FrontierExecutorOrchestrator",
                "All 30 dimension-question executors verified (D1Q1-D6Q5)",
                {
                    "expected": 30,
                    "found": found_count,
                    "dimensions": list(self.DIMENSION_NAMES.items())
                }
            )
        else:
            self.add_finding(
                AuditCategory.EXECUTOR_ARCHITECTURE,
                AuditStatus.FAILED,
                "FrontierExecutorOrchestrator",
                f"Missing executors: expected 30, found {found_count}",
                {
                    "expected": 30,
                    "found": found_count,
                    "missing": [e for e in self.EXPECTED_EXECUTORS if e not in
executor_classes]
                }
            )

        return {
            "status": "VERIFIED" if found_count == 30 else "FAILED",
            "executors_found": found_count,
            "executors_expected": 30,
            "executor_details": executor_audit_info
        }

    def audit_questionnaire_access(self) -> dict[str, Any]:
        """
        Audit questionnaire access patterns to ensure dependency injection.

        Verifies that core scripts:
        1. Do NOT directly access questionnaire_monolith.json
        2. Do NOT instantiate QuestionnaireResourceProvider directly
        3. DO receive questionnaire via dependency injection

        Returns:
            Dictionary with audit results
        """
        logger.info("=" * 80)
        logger.info("AUDITING: Questionnaire Access Patterns (Dependency Injection)")
        logger.info("=" * 80)

        violations = []
        compliant_scripts = []

        for script_name in self.CORE_SCRIPTS:
            # Find the script in processing or analysis directories
            script_paths = [
                self.repo_root / "src/saaaaaa/processing" / script_name,
                self.repo_root / "src/saaaaaa/analysis" / script_name
            ]

            script_path = None
            for path in script_paths:
                if path.exists():
                    script_path = path
                    break

            if not script_path:
                self.add_finding(
                    AuditCategory.QUESTIONNAIRE_ACCESS,
                    AuditStatus.WARNING,
                    script_name,
                    "Script file not found",
                    {"searched_paths": [str(p) for p in script_paths]}
                )
                continue

            # Read and analyze the script
            with open(script_path, encoding='utf-8') as f:
                content = f.read()

            # Check for violations
            has_violations = False
            violation_details = []

            # Check for direct file access
            if 'questionnaire_monolith.json' in content or 'open(' in content and
'questionnaire' in content:
                has_violations = True
                violation_details.append("Direct file access to questionnaire detected")

            # Check for direct instantiation of QuestionnaireResourceProvider
            if 'QuestionnaireResourceProvider(' in content:
                has_violations = True
                violation_details.append("Direct instantiation of
QuestionnaireResourceProvider")

            # Check for load_questionnaire() calls (should only be in factory)
            if 'load_questionnaire()' in content and script_name != 'factory.py':
                has_violations = True
                violation_details.append("Direct call to load_questionnaire()")

            # Verify dependency injection pattern
            uses_dependency_injection = False
            if (
                any(pattern in content for pattern in [
                    'questionnaire: Mapping',
                    'questionnaire: dict',
                ])
                or ('def __init__' in content and 'questionnaire' in content)
                or ('@dataclass' in content and 'questionnaire' in content)
            ):
                uses_dependency_injection = True

            if has_violations:
                violations.append(script_name)
                self.add_finding(
                    AuditCategory.QUESTIONNAIRE_ACCESS,
                    AuditStatus.FAILED,
                    script_name,
                    "Questionnaire access violations detected",
                    {
                        "violations": violation_details,
                        "file": str(script_path)
                    }
                )
            else:
                compliant_scripts.append(script_name)
                self.add_finding(
                    AuditCategory.QUESTIONNAIRE_ACCESS,
                    AuditStatus.VERIFIED,
                    script_name,
                    "Properly uses dependency injection for questionnaire access",
                    {
                        "uses_dependency_injection": uses_dependency_injection,
                        "file": str(script_path)
                    }
                )

        # Check factory.py as the authorized loader
        factory_path = self.repo_root / "src/saaaaaa/core/orchestrator/factory.py"
        if factory_path.exists():
            with open(factory_path, encoding='utf-8') as f:
                factory_content = f.read()

            has_load_function = 'load_questionnaire' in factory_content
            has_provider_creation = 'QuestionnaireResourceProvider' in factory_content

            if has_load_function:
                self.add_finding(
                    AuditCategory.QUESTIONNAIRE_ACCESS,
                    AuditStatus.VERIFIED,
                    "factory.py",
                    "Authorized questionnaire loader verified",
                    {
                        "has_load_function": has_load_function,
                        "has_provider_creation": has_provider_creation
                    }
                )
            else:
                self.add_finding(
                    AuditCategory.QUESTIONNAIRE_ACCESS,
                    AuditStatus.WARNING,
                    "factory.py",
                    "Factory missing questionnaire loading functionality"
                )

        # Overall assessment
        total_scripts = len(self.CORE_SCRIPTS)
        compliant_count = len(compliant_scripts)

        if compliant_count == total_scripts:
            self.add_finding(
                AuditCategory.QUESTIONNAIRE_ACCESS,
                AuditStatus.VERIFIED,
                "Questionnaire Access Policy",
                f"All {total_scripts} core scripts comply with dependency injection
policy",
                {
                    "compliant_scripts": compliant_scripts,
                    "violations": []
                }
            )
        else:
            self.add_finding(
                AuditCategory.QUESTIONNAIRE_ACCESS,
                AuditStatus.FAILED,
                "Questionnaire Access Policy",
                f"Policy violations found: {len(violations)}/{total_scripts} scripts",
                {
                    "compliant_scripts": compliant_scripts,
                    "violations": violations
            }
        )

        return {
            "status": "VERIFIED" if compliant_count == total_scripts else "FAILED",
            "compliant_scripts": compliant_count,
            "total_scripts": total_scripts,
            "violations": violations
        }

    def audit_factory_pattern(self) -> dict[str, Any]:
        """
        Audit factory pattern implementation.

        Verifies:
        1. Primary loader exists: factory.py::load_questionnaire_monolith()
        2. QuestionnaireResourceProvider for dependency injection
        3. No unauthorized direct access

        Returns:
            Dictionary with audit results
        """
        logger.info("=" * 80)
        logger.info("AUDITING: Factory Pattern Implementation")
        logger.info("=" * 80)

        factory_path = self.repo_root / "src/saaaaaa/core/orchestrator/factory.py"
        questionnaire_path = self.repo_root /
"src/saaaaaa/core/orchestrator/questionnaire.py"

        results = {
            "factory_exists": False,
            "has_load_function": False,
            "questionnaire_module_exists": False,
            "has_provider_class": False
        }

        # Check factory.py
        if factory_path.exists():
            results["factory_exists"] = True
            with open(factory_path, encoding='utf-8') as f:
                factory_content = f.read()

            # Parse AST
            try:
                tree = ast.parse(factory_content)

                # Look for load functions
                for node in ast.walk(tree):
                    if isinstance(node, ast.FunctionDef):
                        if 'load_questionnaire' in node.name.lower():
                            results["has_load_function"] = True
                            self.add_finding(
                                AuditCategory.FACTORY_PATTERN,
                                AuditStatus.VERIFIED,
                                f"factory.py::{node.name}",
                                "Questionnaire loader function found",
                                {"line": node.lineno}
                            )
            except SyntaxError as e:
                self.add_finding(
                    AuditCategory.FACTORY_PATTERN,
                    AuditStatus.FAILED,
                    "factory.py",
                    f"Syntax error: {e}"
                )
        else:
            self.add_finding(
                AuditCategory.FACTORY_PATTERN,
                AuditStatus.FAILED,
                "factory.py",
                "Factory file not found",
                {"expected_path": str(factory_path)}
            )

        # Check questionnaire.py
        if questionnaire_path.exists():
            results["questionnaire_module_exists"] = True
            with open(questionnaire_path, encoding='utf-8') as f:
                questionnaire_content = f.read()

            # Parse AST
            try:
                tree = ast.parse(questionnaire_content)

                # Look for QuestionnaireResourceProvider
                for node in ast.walk(tree):
                    if isinstance(node, ast.ClassDef):
                        if 'QuestionnaireResourceProvider' in node.name:
                            results["has_provider_class"] = True
                            self.add_finding(
                                AuditCategory.FACTORY_PATTERN,
                                AuditStatus.VERIFIED,
                                f"questionnaire.py::{node.name}",
                                "QuestionnaireResourceProvider class found",
                                {"line": node.lineno}
                            )
            except SyntaxError as e:
                self.add_finding(
                    AuditCategory.FACTORY_PATTERN,
                    AuditStatus.FAILED,
                    "questionnaire.py",
                    f"Syntax error: {e}"
                )
        else:
            self.add_finding(
                AuditCategory.FACTORY_PATTERN,
                AuditStatus.FAILED,
                "questionnaire.py",
                "Questionnaire module not found",
                {"expected_path": str(questionnaire_path)}
            )

        # Overall assessment
        all_verified = all(results.values())

        if all_verified:
            self.add_finding(
                AuditCategory.FACTORY_PATTERN,
                AuditStatus.VERIFIED,
                "Factory Pattern",
                "Factory pattern fully implemented and verified",
                results
            )
        else:
            self.add_finding(
                AuditCategory.FACTORY_PATTERN,
                AuditStatus.FAILED,
                "Factory Pattern",
                "Factory pattern incomplete or missing components",
                results
            )

        return {
            "status": "VERIFIED" if all_verified else "FAILED",
            **results
        }

    def audit_method_signatures(self) -> dict[str, Any]:
        """
        Audit method signatures across core modules.

        Verifies that all methods have:
        1. Type annotations
        2. Docstrings
        3. Proper parameter documentation

        Returns:
            Dictionary with audit results
        """
        logger.info("=" * 80)
        logger.info("AUDITING: Method Signatures (165 methods across 38 classes)")
        logger.info("=" * 80)

        # Target files to audit
        target_files = [
            self.repo_root / "src/saaaaaa/processing" / script
            for script in self.CORE_SCRIPTS
        ] + [
            self.repo_root / "src/saaaaaa/analysis" / script
            for script in self.CORE_SCRIPTS
        ]

        total_methods = 0
        complete_methods = 0
        incomplete_methods = []

        for file_path in target_files:
            if not file_path.exists():
                continue

            with open(file_path, encoding='utf-8') as f:
                content = f.read()

            try:
                tree = ast.parse(content)

                for node in ast.walk(tree):
                    if isinstance(node, ast.ClassDef):
                        class_name = node.name

                        for item in node.body:
                            if isinstance(item, ast.FunctionDef):
                                total_methods += 1
                                method_name = item.name

                                # Check for type annotations
                                has_return_annotation = item.returns is not None
                                has_param_annotations = all(
                                    arg.annotation is not None
                                    for arg in item.args.args
                                    if arg.arg != 'self'
                                )

                                # Check for docstring
                                has_docstring = (
                                    ast.get_docstring(item) is not None
                                )

                                is_complete = (
                                    has_return_annotation and
                                    has_param_annotations and
                                    has_docstring
                                )
                        if is_complete:
                            complete_methods += 1
                        else:
                            incomplete_methods.append({
                                "file": file_path.name,
                                "class": class_name,
                                "method": method_name,
                                "line": item.lineno,
                                "missing": {
                                    "return_annotation": not
    has_return_annotation,
                                    "param_annotations": not
    has_param_annotations,
                                    "docstring": not has_docstring
                                }
                            })
            except SyntaxError as e:
                logger.warning(f"Syntax error in {file_path}: {e}")

        # Assessment
        completion_rate = (complete_methods / total_methods * 100) if total_methods > 0
    else 0

        if completion_rate == 100:
            self.add_finding(
                AuditCategory.METHOD_SIGNATURES,
                AuditStatus.VERIFIED,
                "Method Signatures",
                f"All {total_methods} methods have complete signatures",
                {
                    "total": total_methods,
                    "complete": complete_methods,
                    "completion_rate": completion_rate
                }
            )
        elif completion_rate >= 90:
            self.add_finding(
                AuditCategory.METHOD_SIGNATURES,
                AuditStatus.WARNING,
                "Method Signatures",
                f"Most methods complete ({completion_rate:.1f}%), but
    {len(incomplete_methods)} need attention",
                {
                    "total": total_methods,
                    "complete": complete_methods,
                    "incomplete": len(incomplete_methods),
                    "completion_rate": completion_rate
                }
            )
        else:
            self.add_finding(
                AuditCategory.METHOD_SIGNATURES,
                AuditStatus.FAILED,
                "Method Signatures",
                f"Insufficient completion rate ({completion_rate:.1f}%)",
                {
                    "total": total_methods,
                    "complete": complete_methods,
                    "incomplete": len(incomplete_methods),
                    "completion_rate": completion_rate,
                    "incomplete_methods": incomplete_methods[:10]  # First 10
                }
            )

        return {
            "status": "VERIFIED" if completion_rate == 100 else ("WARNING" if
    completion_rate >= 90 else "FAILED"),
            "total_methods": total_methods,
            "complete_methods": complete_methods,
            "completion_rate": completion_rate,
            "incomplete_methods": incomplete_methods
        }

    def audit_configuration_system(self) -> dict[str, Any]:
        """
        Audit configuration system for type-safety and parameters.

        Verifies:
        1. ExecutorConfig with proper parameter ranges
        2. AdvancedModuleConfig with academic parameters
        3. Type-safety with Pydantic
        4. BLAKE3 fingerprinting

        Returns:
            Dictionary with audit results
        """
        logger.info("=" * 80)
        logger.info("AUDITING: Configuration System (Type-Safety & Parameters)")
        logger.info("=" * 80)

        config_files = {
            "executor_config": self.repo_root /
"src/saaaaaa/core/orchestrator/executor_config.py",
            "advanced_module_config": self.repo_root /
"src/saaaaaa/core/orchestrator/advanced_module_config.py"
        }

        results = {}

        for config_name, config_path in config_files.items():
            if not config_path.exists():
                self.add_finding(
                    AuditCategory.CONFIGURATION_SYSTEM,
                    AuditStatus.FAILED,
                    config_name,
                    "Configuration file not found",
                    {"expected_path": str(config_path)}
                )
                results[config_name] = False
                continue

            with open(config_path, encoding='utf-8') as f:
                content = f.read()

            # Check for Pydantic BaseModel
            has_pydantic = 'BaseModel' in content or 'pydantic' in content
            has_field_validation = 'Field(' in content or 'validator' in content
            has_frozen = 'frozen=True' in content or 'class Config' in content

            if has_pydantic and has_field_validation:
                self.add_finding(
                    AuditCategory.CONFIGURATION_SYSTEM,
                    AuditStatus.VERIFIED,
                    config_name,
                    "Type-safe configuration with Pydantic validation",
                    {
                        "has_pydantic": has_pydantic,
                        "has_field_validation": has_field_validation,
                        "has_frozen": has_frozen
                    }
                )
                results[config_name] = True
            else:
                self.add_finding(
                    AuditCategory.CONFIGURATION_SYSTEM,
                    AuditStatus.WARNING,
                    config_name,
                    "Configuration lacks proper type-safety features",
                    {
                        "has_pydantic": has_pydantic,
                        "has_field_validation": has_field_validation,
                        "has_frozen": has_frozen
                    }
                )
                results[config_name] = False

        # Overall assessment
        all_verified = all(results.values())

        if all_verified:
            self.add_finding(
                AuditCategory.CONFIGURATION_SYSTEM,
                AuditStatus.VERIFIED,
                "Configuration System",
                "All configuration modules are type-safe and properly validated",
                results
            )
        else:
            self.add_finding(
                AuditCategory.CONFIGURATION_SYSTEM,
                AuditStatus.WARNING,
                "Configuration System",
                "Some configuration modules need improvement",
                results
            )

        return {
            "status": "VERIFIED" if all_verified else "WARNING",
            **results
        }

    def generate_audit_report(self, output_path: Path | None = None) -> dict[str, Any]:
        """
        Generate comprehensive audit report.

        Args:
            output_path: Optional path to save the report

        Returns:
            Complete audit report as dictionary
        """
        logger.info("=" * 80)
        logger.info("GENERATING COMPREHENSIVE AUDIT REPORT")
        logger.info("=" * 80)

        # Run all audits
        executor_results = self.audit_executor_architecture()
        questionnaire_results = self.audit_questionnaire_access()
        factory_results = self.audit_factory_pattern()
        method_results = self.audit_method_signatures()
        config_results = self.audit_configuration_system()

        # Compile report
        report = {
            "audit_metadata": {
                "timestamp": datetime.utcnow().isoformat(),
                "repository_root": str(self.repo_root),
                "total_findings": len(self.findings)
            },
            "audit_results": {
                "executor_architecture": executor_results,
                "questionnaire_access": questionnaire_results,
                "factory_pattern": factory_results,
                "method_signatures": method_results,
                "configuration_system": config_results
            },
            "findings": [f.to_dict() for f in self.findings],
            "summary": self._generate_summary()
        }

        # Save report if path provided
        if output_path:
            output_path.parent.mkdir(parents=True, exist_ok=True)
            with open(output_path, 'w', encoding='utf-8') as f:
                json.dump(report, f, indent=2)
            logger.info(f"Audit report saved to: {output_path}")

        return report

    def _generate_summary(self) -> dict[str, Any]:
        """Generate summary of audit findings."""
        summary = {
            "total_findings": len(self.findings),
            "verified": sum(1 for f in self.findings if f.status == AuditStatus.VERIFIED),
            "warnings": sum(1 for f in self.findings if f.status == AuditStatus.WARNING),
            "failed": sum(1 for f in self.findings if f.status == AuditStatus.FAILED),
            "by_category": {}
        }

        # Group by category
        for category in AuditCategory:
            category_findings = [f for f in self.findings if f.category == category]
            summary["by_category"][category.value] = {
                "total": len(category_findings),
                "verified": sum(1 for f in category_findings if f.status ==
AuditStatus.VERIFIED),
                "warnings": sum(1 for f in category_findings if f.status ==
AuditStatus.WARNING),
                "failed": sum(1 for f in category_findings if f.status ==
AuditStatus.FAILED)
            }

        return summary

    def print_summary(self) -> None:
        """Print audit summary to console."""
        summary = self._generate_summary()

        print("\n" + "=" * 80)
        print("📋 AUDIT SUMMARY")
        print("=" * 80)
        print(f"Total Findings: {summary['total_findings']}")
        print(f"  ✓ Verified: {summary['verified']}")
        print(f"  ⚠  Warnings: {summary['warnings']}")
        print(f"  ✗ Failed: {summary['failed']}")
        print("\n" + "-" * 80)
        print("By Category:")
        print("-" * 80)

        for category, stats in summary["by_category"].items():
            if stats["total"] > 0:
                print(f"\n{category}:")
                print(f"  Total: {stats['total']}")
                print(f"  ✓ Verified: {stats['verified']}")
                print(f"  ⚠  Warnings: {stats['warnings']}")
                print(f"  ✗ Failed: {stats['failed']}")

        print("\n" + "=" * 80)


def main() -> None:
    """Main entry point for audit system."""
    import argparse

    parser = argparse.ArgumentParser(description="FARFAN Pipeline Audit System")
    parser.add_argument(
        "--repo-root",
        type=Path,
        default=PROJECT_ROOT,
        help="Repository root directory"
    )
    parser.add_argument(
        "--output",
        type=Path,
        help="Output path for audit report (JSON)"
    )
    parser.add_argument(
        "--verbose",
        action="store_true",
        help="Enable verbose logging"
    )

    args = parser.parse_args()

    # Configure logging
    logging.basicConfig(
        level=logging.DEBUG if args.verbose else logging.INFO,
        format='%(asctime)s - %(name)s - %(levelname)s - %(message)s'
    )

    # Run audit
    audit_system = AuditSystem(args.repo_root)
    report = audit_system.generate_audit_report(args.output)
    audit_system.print_summary()

    # Exit with appropriate code
    if report["summary"]["failed"] > 0:
        sys.exit(1)
    elif report["summary"]["warnings"] > 0:
        sys.exit(2)
    else:
        sys.exit(0)


if __name__ == "__main__":
    main()

===== FILE: src/saaaaaa/compat/__init__.py =====
"""
Compatibility Layer - Version Shims and Polyfills

This module provides a unified interface for Python version differences
and third-party package variations. All version-specific imports should
go through this layer.

Shims provided:
- tomllib/tomli (TOML parsing, Python 3.11+ vs earlier)
- importlib.resources (files() API, Python 3.9+ vs earlier)
- typing extensions (backports for older Python)
- typing (future annotations support)

Design:
- Explicit imports only (no star imports)
- Fail-fast on missing required compatibility
- Clear error messages with version requirements
"""

from __future__ import annotations
```

```
import sys
from typing import Any

# Lazy loading utilities for heavy dependencies
from .lazy_deps import (
    get_numpy,
    get_pandas,
    get_polars,
    get_pyarrow,
    get_spacy,
    get_torch,
    get_transformers,
)
from .safe_imports import (
    ImportErrorDetailed,
    check_import_available,
    get_import_version,
    lazy_import,
    try_import,
)

# Backward compatibility alias
OptionalDependencyError = ImportErrorDetailed

# Re-export safe import utilities and lazy deps
__all__ = [
    # Core import utilities
    "ImportErrorDetailed",
    "OptionalDependencyError",  # Backward compatibility alias
    "try_import",
    "lazy_import",
    "check_import_available",
    "get_import_version",
    # Version compatibility shims
    "tomllib",
    "resources_files",
    # Lazy loading utilities
    "get_numpy",
    "get_pandas",
    "get_polars",
    "get_pyarrow",
    "get_torch",
    "get_transformers",
    "get_spacy",
]


# ============================================================================
# TOML Parsing - Python 3.11+ tomllib vs tomli
# ============================================================================

if sys.version_info >= (3, 11):
    import tomllib
else:
    # Python < 3.11 needs tomli package
    # try_import with required=True will raise if missing
    tomllib = try_import(  # type: ignore[assignment]
        "tomli",
        required=True,
        hint="Python < 3.11 requires 'tomli' package. Install with: pip install tomli",
    )


# ============================================================================
# Importlib Resources - Python 3.9+ files() vs older resource API
# ============================================================================

try:
    from importlib.resources import files as resources_files
except ImportError:
    # Python < 3.9 needs importlib_resources backport
    # try_import with required=True will raise if missing
    _resources = try_import(
        "importlib_resources",
        required=True,
        hint="Python < 3.9 requires 'importlib_resources'. "
             "Install with: pip install importlib-resources",
    )
    resources_files = _resources.files  # type: ignore[attr-defined]


# ============================================================================
# Typing Extensions - Backports for older Python versions
# ============================================================================

# For maximum compatibility, we always try to import typing_extensions
# Even on Python 3.10+, typing_extensions provides latest features
_typing_extensions_available = check_import_available("typing_extensions")

if _typing_extensions_available:
    import typing_extensions

    # Use typing_extensions versions if available (they're usually more up-to-date)
    TypeAlias = typing_extensions.TypeAlias
    ParamSpec = typing_extensions.ParamSpec
    Concatenate = typing_extensions.Concatenate
    Literal = typing_extensions.Literal
    Protocol = typing_extensions.Protocol
    TypedDict = typing_extensions.TypedDict
    Final = typing_extensions.Final
    Annotated = typing_extensions.Annotated

else:
    # Fall back to stdlib typing
    # This may not have all features on older Python versions
    # TypeAlias added in 3.10
    from typing import (  # type: ignore[misc, assignment]
        Annotated,  # 3.9+
        Concatenate,
        Final,  # 3.8+
        Literal,  # 3.8+
        ParamSpec,
        Protocol,  # 3.8+
        TypeAlias,
        TypedDict,  # 3.8+
    )


# ============================================================================
# Platform Detection Utilities
# ============================================================================

def get_platform_info() -> dict[str, Any]:
    """
    Get comprehensive platform information for debugging.

    Returns
    -------
    dict[str, Any]
        Platform details including OS, architecture, Python version

    Examples
    --------
    >>> info = get_platform_info()
    >>> print(f"Running on {info['system']} {info['architecture']}")
    """
    import platform

    return {
        "system": platform.system(),
        "release": platform.release(),
        "version": platform.version(),
        "architecture": platform.machine(),
        "python_version": sys.version,
        "python_implementation": platform.python_implementation(),
        "python_version_tuple": sys.version_info[:3],
    }


def check_minimum_python_version(major: int, minor: int) -> bool:
    """
    Check if Python version meets minimum requirement.

    Parameters
    ----------
    major : int
        Required major version
    minor : int
        Required minor version

    Returns
    -------
    bool
        True if current version >= required version

    Examples
    --------
    >>> if not check_minimum_python_version(3, 10):
    ...     raise RuntimeError("Python 3.10+ required")
    """
    return sys.version_info >= (major, minor)


# ============================================================================
# Validation on Import
# ============================================================================

# Ensure minimum Python version (as specified in pyproject.toml)
if not check_minimum_python_version(3, 10):
    raise ImportErrorDetailed(
        f"Python 3.10 or later required. Current version: {sys.version}. "
        "Please upgrade Python or use a compatible environment."
    )

===== FILE: src/saaaaaa/compat/lazy_deps.py =====
"""
Lazy Loading for Heavy Dependencies

This module provides lazy-loaded imports for heavy optional dependencies
to reduce import-time overhead and improve startup performance.

Heavy dependencies include:
- polars: Fast DataFrame library (50-200ms import time)
- pyarrow: Arrow format support (50-150ms import time)
- torch: Deep learning framework (500-1500ms import time)
- tensorflow: Machine learning framework (1000-3000ms import time)
- transformers: NLP models (200-500ms import time)
- spacy: NLP processing (200-400ms import time)

Usage:
    from saaaaaa.compat.lazy_deps import get_polars, get_pyarrow

    def process_dataframe(data):
        pl = get_polars()  # Lazy-loaded on first call
        return pl.DataFrame(data)
"""

from __future__ import annotations

from typing import Any

from .safe_imports import lazy_import


def get_polars() -> Any:
    """
    Lazy-load polars library.

    Returns
    -------
    module
        The polars module

    Raises
    ------
    ImportErrorDetailed
        If polars is not installed

    Examples
    --------
    >>> pl = get_polars()
    >>> df = pl.DataFrame({"a": [1, 2, 3]})
    """
    return lazy_import(
        "polars",
        hint="Install with: pip install polars\n"
             "Or install analytics extra: pip install saaaaaa[analytics]"
    )


def get_pyarrow() -> Any:
    """
    Lazy-load pyarrow library.

    Returns
    -------
    module
        The pyarrow module

    Raises
    ------
    ImportErrorDetailed
        If pyarrow is not installed

    Examples
    --------
    >>> pa = get_pyarrow()
    >>> table = pa.table({"a": [1, 2, 3]})
    """
    return lazy_import(
        "pyarrow",
        hint="Install with: pip install pyarrow\n"
             "This is a core dependency for Arrow format support."
    )


def get_torch() -> Any:
    """
    Lazy-load torch library.

    Returns
    -------
    module
        The torch module

    Raises
    ------
    ImportErrorDetailed
        If torch is not installed

    Examples
    --------
    >>> torch = get_torch()
    >>> tensor = torch.tensor([1, 2, 3])
    """
    return lazy_import(
        "torch",
        hint="Install with: pip install torch\n"
             "Or install ml extra: pip install saaaaaa[ml]"
    )


def get_tensorflow() -> Any:
    """
    Lazy-load tensorflow library.

    Returns
    -------
    module
        The tensorflow module

    Raises
    ------
    ImportErrorDetailed
        If tensorflow is not installed

    Examples
    --------
    >>> tf = get_tensorflow()
    >>> tensor = tf.constant([1, 2, 3])
    """
    return lazy_import(
        "tensorflow",
        hint="Install with: pip install tensorflow\n"
             "Or install ml extra: pip install saaaaaa[ml]"
    )


def get_transformers() -> Any:
    """
    Lazy-load transformers library.

    Returns
    -------
    module
        The transformers module

    Raises
    ------
    ImportErrorDetailed
        If transformers is not installed

    Examples
    --------
    >>> transformers = get_transformers()
    >>> model = transformers.AutoModel.from_pretrained("bert-base-uncased")
    """
    return lazy_import(
        "transformers",
        hint="Install with: pip install transformers\n"
```

```
            "Or install nlp extra: pip install saaaaaa[nlp]"
    )


def get_spacy() -> Any:
    """
    Lazy-load spacy library.

    Returns
    -------
    module
        The spacy module

    Raises
    ------
    ImportErrorDetailed
        If spacy is not installed

    Examples
    --------
    >>> spacy = get_spacy()
    >>> nlp = spacy.load("es_core_news_sm")
    """
    return lazy_import(
        "spacy",
        hint="Install with: pip install spacy\n"
            "Then download language model: python -m spacy download es_core_news_sm\n"
            "Or install nlp extra: pip install saaaaaa[nlp]"
    )


def get_pandas() -> Any:
    """
    Lazy-load pandas library.

    This is typically a required dependency but we lazy-load it
    to reduce import-time overhead.

    Returns
    -------
    module
        The pandas module

    Raises
    ------
    ImportErrorDetailed
        If pandas is not installed

    Examples
    --------
    >>> pd = get_pandas()
    >>> df = pd.DataFrame({"a": [1, 2, 3]})
    """
    return lazy_import(
        "pandas",
        hint="Install with: pip install pandas\n"
            "This is a core dependency."
    )


def get_numpy() -> Any:
    """
    Lazy-load numpy library.

    This is typically a required dependency but we lazy-load it
    to reduce import-time overhead in modules that don't always need it.

    Returns
    -------
    module
        The numpy module

    Raises
    ------
    ImportErrorDetailed
        If numpy is not installed

    Examples
    --------
    >>> np = get_numpy()
    >>> array = np.array([1, 2, 3])
    """
    return lazy_import(
        "numpy",
        hint="Install with: pip install numpy\n"
             "This is a core dependency."
    )


# Convenience mapping for programmatic access
LAZY_DEPS = {
    "polars": get_polars,
    "pyarrow": get_pyarrow,
    "torch": get_torch,
    "tensorflow": get_tensorflow,
    "transformers": get_transformers,
    "spacy": get_spacy,
    "pandas": get_pandas,
    "numpy": get_numpy,
}


def get_lazy_dep(name: str) -> Any:
    """
    Get a lazy-loaded dependency by name.

    Parameters
    ----------
    name : str
        Name of the dependency (e.g., "polars", "torch")

    Returns
    -------
    module
        The requested module

    Raises
    ------
    KeyError
        If the dependency name is not recognized
    ImportErrorDetailed
        If the dependency is not installed

    Examples
    --------
    >>> polars = get_lazy_dep("polars")
    >>> torch = get_lazy_dep("torch")
    """
    if name not in LAZY_DEPS:
        raise KeyError(
            f"Unknown lazy dependency: {name}. "
            f"Available: {', '.join(LAZY_DEPS.keys())}"
        )

    return LAZY_DEPS[name]()
```

```
__all__ = [
    "get_polars",
    "get_pyarrow",
    "get_torch",
    "get_tensorflow",
    "get_transformers",
    "get_spacy",
    "get_pandas",
    "get_numpy",
    "get_lazy_dep",
    "LAZY_DEPS",
]

===== FILE: src/saaaaaa/compat/native_check.py =====
"""
Native Extension and System Library Verification

This module checks for C-extensions, native libraries, and platform-specific
requirements to provide early detection and clear error messages.

Checks include:
- Wheel compatibility (manylinux, musllinux, macosx, win)
- System libraries (libzstd, icu, libomp, libstdc++)
- CPU features (AVX, NEON for polars/arrow)
- FIPS mode detection for cryptography
"""

from __future__ import annotations

import os
import platform
import subprocess
import sys
from dataclasses import dataclass
from pathlib import Path


@dataclass
class NativeCheckResult:
    """Result of a native library or extension check."""

    available: bool
    message: str
    hint: str = ""


def check_system_library(libname: str) -> NativeCheckResult:
    """
    Check if a system library is available.

    Parameters
    ----------
    libname : str
        Library name (e.g., 'zstd', 'icu', 'omp')

    Returns
    -------
    NativeCheckResult
        Result with availability and guidance

    Examples
    --------
    >>> result = check_system_library('zstd')
    >>> if not result.available:
    ...     print(result.hint)
    """
    system = platform.system()
    if system == "Linux":
        # Try ldconfig or direct file check
        try:
            result = subprocess.run(
                ["ldconfig", "-p"],
                check=False, capture_output=True,
                text=True,
                timeout=5,
            )
            if libname in result.stdout:
                return NativeCheckResult(
                    available=True,
                    message=f"Library {libname} found via ldconfig",
                )
        except (subprocess.SubprocessError, FileNotFoundError):
            pass

        # Fallback: check common lib paths
        base_root = Path(os.sep)
        common_paths = [
            base_root / "usr" / "lib" / f"lib{libname}.so",
            base_root / "usr" / "lib" / "x86_64-linux-gnu" / f"lib{libname}.so",
            base_root / "usr" / "local" / "lib" / f"lib{libname}.so",
        ]
        for path in common_paths:
            if path.exists():
                return NativeCheckResult(
                    available=True,
                    message=f"Library {libname} found at {path}",
                )

        return NativeCheckResult(
            available=False,
            message=f"Library {libname} not found",
            hint=f"Install system package: apt-get install lib{libname}-dev
(Debian/Ubuntu) "
                 f"or yum install {libname}-devel (RHEL/CentOS)",
        )

    elif system == "Darwin":
        # macOS - check via dyld
        try:
            result = subprocess.run(
                ["otool", "-L", sys.executable],
                check=False, capture_output=True,
                text=True,
                timeout=5,
            )
            if libname in result.stdout:
                return NativeCheckResult(
                    available=True,
                    message=f"Library {libname} found via otool",
                )
        except (subprocess.SubprocessError, FileNotFoundError):
            pass

        return NativeCheckResult(
            available=False,
            message=f"Library {libname} not found",
            hint=f"Install via Homebrew: brew install {libname}",
        )

    elif system == "Windows":
        # Windows - check PATH and common locations
        for path_dir in os.environ.get("PATH", "").split(os.pathsep):
            dll_path = Path(path_dir) / f"{libname}.dll"
            if dll_path.exists():
```

```
            return NativeCheckResult(
                available=True,
                message=f"Library {libname}.dll found at {dll_path}",
            )

        return NativeCheckResult(
            available=False,
            message=f"Library {libname}.dll not found in PATH",
            hint=f"Install {libname} and add to PATH",
        )

    return NativeCheckResult(
        available=False,
        message=f"Cannot check library {libname} on {system}",
        hint="Platform detection not implemented for this system",
    )


def check_wheel_compatibility(package: str) -> NativeCheckResult:
    """
    Check if a package has appropriate wheels for the current platform.

    Parameters
    ----------
    package : str
        Package name (e.g., 'pyarrow', 'polars')

    Returns
    -------
    NativeCheckResult
        Compatibility status and guidance
    """
    system = platform.system()
    platform.machine()

    # Platform tags we expect
    if system in {"Linux", "Darwin", "Windows"}:
        pass

    try:
        # Try to import and check __file__ for wheel origin
        import importlib
        mod = importlib.import_module(package)
        if hasattr(mod, "__file__") and mod.__file__:
            file_path = mod.__file__
            # Check if installed from wheel (dist-info present)
            if "site-packages" in file_path:
                return NativeCheckResult(
                    available=True,
                    message=f"Package {package} installed from wheel",
                )

        return NativeCheckResult(
            available=True,
            message=f"Package {package} available (source install or wheel)",
            hint="Consider using pre-built wheels for better compatibility",
        )
    except ImportError:
        return NativeCheckResult(
            available=False,
            message=f"Package {package} not installed",
            hint=f"Install with: pip install {package}",
        )


def check_cpu_features() -> NativeCheckResult:
    """
    Check CPU features required by performance libraries.
    Some packages (polars, pyarrow) require specific CPU instructions.

    Returns
    -------
    NativeCheckResult
        CPU feature availability
    """
    machine = platform.machine().lower()

    # Basic architecture check
    if machine in ("x86_64", "amd64"):
        # Would need cpuinfo or similar for detailed AVX detection
        # For now, assume modern x86_64 has basic features
        return NativeCheckResult(
            available=True,
            message=f"CPU architecture {machine} is supported",
        )
    elif machine in ("arm64", "aarch64"):
        return NativeCheckResult(
            available=True,
            message=f"CPU architecture {machine} (ARM) is supported",
        )
    else:
        return NativeCheckResult(
            available=False,
            message=f"CPU architecture {machine} may not be supported",
            hint="Some packages require x86_64 or ARM64. Check package documentation.",
        )


def check_fips_mode() -> bool:
    """
    Detect if system is in FIPS mode (Federal Information Processing Standards).

    This affects cryptography backend selection.

    Returns
    -------
    bool
        True if FIPS mode is enabled
    """
    if platform.system() == "Linux":
        # Check /proc/sys/crypto/fips_enabled
        try:
            with open("/proc/sys/crypto/fips_enabled") as f:
                return f.read().strip() == "1"
        except (FileNotFoundError, PermissionError):
            pass

    return False


def verify_native_dependencies(packages: list[str]) -> dict[str, NativeCheckResult]:
    """
    Verify native dependencies for a list of packages.

    Parameters
    ----------
    packages : list[str]
        Package names to verify

    Returns
    -------
    dict[str, NativeCheckResult]
        Mapping of package name to verification result

    Examples
    --------
    >>> results = verify_native_dependencies(['pyarrow', 'polars'])
    >>> for pkg, result in results.items():
    ...     if not result.available:
    ...         print(f"{pkg}: {result.hint}")
    """
    results = {}

    # Known native dependencies
    native_deps = {
        "pyarrow": ["zstd"],
        "polars": [],  # Statically linked
        "blake3": [],  # Statically linked
    }

    for package in packages:
        # Check package itself
        results[package] = check_wheel_compatibility(package)

        # Check system libraries
        if package in native_deps:
            for lib in native_deps[package]:
                lib_result = check_system_library(lib)
                if not lib_result.available:
                    results[f"{package}:{lib}"] = lib_result

    return results


def print_native_report() -> None:
    """
    Print a comprehensive native environment report.

    This is useful for debugging environment issues.
    """
    print("=== Native Environment Report ===")
    print(f"Platform: {platform.system()} {platform.release()}")
    print(f"Architecture: {platform.machine()}")
    print(f"Python: {sys.version}")
    print()

    print("CPU Features:")
    cpu_result = check_cpu_features()
    print(f"  {cpu_result.message}")
    print()

    print("FIPS Mode:")
    print(f"  {'Enabled' if check_fips_mode() else 'Disabled'}")
    print()

    print("Critical Packages:")
    packages = ["pyarrow", "polars", "blake3"]
    results = verify_native_dependencies(packages)
    for name, result in results.items():
        status = "✓" if result.available else "✗"
        print(f"  {status} {name}: {result.message}")
        if result.hint:
            print(f"     Hint: {result.hint}")
    print()

    print("System Libraries:")
    for lib in ["zstd", "icu", "omp"]:
        result = check_system_library(lib)
        status = "✓" if result.available else "✗"
        print(f"  {status} {lib}: {result.message}")
        if result.hint:
            print(f"     Hint: {result.hint}")
```

```
if __name__ == "__main__":
    print_native_report()

===== FILE: src/saaaaaa/compat/safe_imports.py =====
"""
Safe Import System - Deterministic, Auditable, Portable

This module implements the core import safety layer for the SAAAAAA system.
All imports in the codebase should use this pattern for optional dependencies,
ensuring fail-fast behavior, clear error messages, and no graceful degradation.

Design Principles:
- No silent failures - imports either succeed completely or fail loudly
- No graceful degradation - partial functionality is rejected
- Deterministic behavior - same inputs always produce same outputs
- Explicit error messages with installation hints
- Support for alternative packages (e.g., tomllib vs tomli)
"""

from __future__ import annotations

import importlib
import sys
from typing import TYPE_CHECKING

if TYPE_CHECKING:
    import types


class ImportErrorDetailed(ImportError):
    """
    Enhanced import error with context and actionable guidance.

    This exception is raised when a required import fails and provides:
    - The module that failed to import
    - Installation instructions or hints
    - Alternative packages if available
    - Context about why the import is needed
    """

    def __init__(self, module_name: str, hint: str = "", install_cmd: str = "") -> None:
        """
        Initialize detailed import error.

        Parameters
        ----------
        module_name : str
            Name of the module that failed to import
        hint : str, optional
            Human-readable context about why this module is needed
        install_cmd : str, optional
            Installation command to resolve the missing dependency
        """
        parts = [f"Failed to import '{module_name}'"]

        if hint:
            parts.append(f"Context: {hint}")

        if install_cmd:
            parts.append(f"Install with: {install_cmd}")

        message = ". ".join(parts)
        super().__init__(message)

        self.module_name = module_name
        self.hint = hint
        self.install_cmd = install_cmd
```

```
def try_import(
    modname: str,
    *,
    required: bool = False,
    hint: str = "",
    alt: str | None = None,
) -> types.ModuleType | None:
    """
    Attempt to import a module with explicit error handling and guidance.

    This function provides controlled import behavior with clear failure modes:
    - Required imports fail immediately with detailed errors
    - Optional imports log warnings and return None
    - Alternative packages are tried if primary fails
    - All failures include installation hints

    Parameters
    ----------
    modname : str
        The fully qualified module name to import (e.g., 'httpx', 'polars')
    required : bool, default=False
        If True, raises ImportErrorDetailed on failure
        If False, logs to stderr and returns None
    hint : str, default=""
        Human-readable guidance for resolving the import failure
        Should include installation command or extra flag
        Example: "Install extra 'http_signals' or set source=memory://"
    alt : str | None, default=None
        Alternative module to try if primary fails
        Example: 'tomli' as alternative to 'tomllib'

    Returns
    -------
    types.ModuleType | None
        The imported module if successful, None if optional and failed

    Raises
    ------
    ImportErrorDetailed
        When required=True and import fails (including alternatives)

    Examples
    --------
    >>> # Optional dependency with hint
    >>> httpx = try_import("httpx", required=False, hint="Install extra 'http_signals'")
    >>> if httpx is None:
    ...     # Use memory:// source instead
    ...     pass

    >>> # Required dependency
    >>> pyarrow = try_import("pyarrow", required=True, hint="Install core runtime")

    >>> # Version-specific with fallback
    >>> toml = try_import("tomllib", alt="tomli", required=True,
    ...                   hint="Python<3.11 needs 'tomli'")

    Notes
    -----
    - This function must NEVER silently substitute mock objects
    - Failure modes must be explicit and actionable
    - Import-time side effects in target modules are NOT controlled here
    - This is NOT for lazy loading - use separate lazy_import() for that
    """
    try:
        return importlib.import_module(modname)
    except Exception as primary_error:
        msg = f"[IMPORT] Failed '{modname}'"

        # Try alternative package if specified
        if alt:
            try:
                return importlib.import_module(alt)
            except Exception as alt_error:
                # Both primary and alternative failed
                combined_error = ImportErrorDetailed(
                    modname, hint=f"{hint}; alternative '{alt}' also failed"
                )
                combined_error.__cause__ = alt_error

                if required:
                    raise combined_error from primary_error
                else:
                    sys.stderr.write(f"{msg} (optional); alt also failed. {hint}\n")
                    return None

        # Required import failed - abort immediately
        if required:
            raise ImportErrorDetailed(modname, hint=hint) from primary_error

        # Optional dependency: log and defer failure to call site
        # This allows the module to load but fail when the feature is used
        sys.stderr.write(f"{msg} (optional). {hint}\n")
        return None


def check_import_available(modname: str) -> bool:
    """
    Check if a module can be imported without actually importing it.

    This is useful for feature flags and conditional code paths without
    triggering import-time side effects.

    Parameters
    ----------
    modname : str
        The fully qualified module name to check

    Returns
    -------
    bool
        True if module can be imported, False otherwise

    Examples
    --------
    >>> if check_import_available("polars"):
    ...     # Use polars backend
    ...     pass
    >>> else:
    ...     # Fall back to pandas
    ...     pass
    """
    try:
        spec = importlib.util.find_spec(modname)
        return spec is not None
    except (ImportError, ModuleNotFoundError, ValueError, AttributeError):
        return False


def get_import_version(modname: str) -> str | None:
    """
    Get the version of an installed module without importing it.

    This uses metadata inspection to avoid import-time side effects.
    Parameters
    ----------
    modname : str
        The module/package name

    Returns
    -------
    str | None
        Version string if available, None otherwise

    Examples
    --------
    >>> get_import_version("numpy")
    '1.26.4'
    """
    try:
        # Python 3.8+ has importlib.metadata
        from importlib.metadata import version  # type: ignore
        return version(modname)
    except Exception:
        return None


# Cache for lazy-loaded modules to ensure deterministic re-import
_lazy_cache: dict[str, types.ModuleType | None] = {}


def lazy_import(modname: str, *, hint: str = "") -> types.ModuleType:
    """
    Lazy-load a module with memoization for deterministic behavior.

    This is for import-time budget optimization on heavy modules.
    Use this in functions that are called infrequently or in cold paths.

    Parameters
    ----------
    modname : str
        Module to lazy-load
    hint : str, default=""
        Installation hint if import fails

    Returns
    -------
    types.ModuleType
        The imported module (cached after first call)

    Raises
    ------
    ImportErrorDetailed
        If the module cannot be imported

    Examples
    --------
    >>> def to_arrow(df):
    ...     pa = lazy_import("pyarrow", hint="Install core runtime")
    ...     return pa.table(df)

    Notes
    -----
    - Memoization ensures the module is only loaded once
    - Cache is module-global, not process-global
    - This does NOT avoid import-time side effects, just defers them
    """
    if modname in _lazy_cache:
        cached = _lazy_cache[modname]
        if cached is None:
            raise ImportErrorDetailed(f"[IMPORT] Module '{modname}' previously failed")
        return cached
    try:
        mod = importlib.import_module(modname)
        _lazy_cache[modname] = mod
        return mod
    except Exception as e:
        _lazy_cache[modname] = None
        msg = f"[IMPORT] Failed lazy import of '{modname}'"
        if hint:
            msg += f". {hint}"
        raise ImportErrorDetailed(msg) from e

===== FILE: src/saaaaaa/concurrency/__init__.py =====
"""
Concurrency module for deterministic parallel execution.

This module provides a deterministic WorkerPool for parallel task execution
with controlled max_workers, backoff, abortability, and per-task instrumentation.
"""

from .concurrency import (
    TaskExecutionError,
    TaskMetrics,
    TaskResult,
    TaskStatus,
    WorkerPool,
    WorkerPoolConfig,
)

__all__ = [
    "WorkerPool",
    "TaskResult",
    "WorkerPoolConfig",
    "TaskExecutionError",
    "TaskStatus",
    "TaskMetrics",
]

===== FILE: src/saaaaaa/concurrency/concurrency.py =====
"""
Concurrency Module - Deterministic Worker Pool for Parallel Execution.

This module implements a deterministic WorkerPool for executing tasks in parallel
with the following features:
- Controlled max_workers for resource management
- Exponential backoff for retries
- Abortability for canceling pending tasks
- Per-task instrumentation and logging
- No race conditions or unwanted variability

Preconditions:
- Tasks and workers are declared before execution
- Each task is idempotent and thread-safe

Invariants:
- No interference between workers
- Deterministic task execution order within priority groups
- Thread-safe state management

Postconditions:
- Pool is usable by orchestrator/choreographer
- All resources are properly cleaned up
- No race conditions or variability in results
"""

from __future__ import annotations

import logging
import threading
import time
from concurrent.futures import Future, ThreadPoolExecutor, as_completed
from dataclasses import dataclass
from enum import Enum
from typing import TYPE_CHECKING, Any
from uuid import uuid4

if TYPE_CHECKING:
    from collections.abc import Callable

logger = logging.getLogger(__name__)

class TaskStatus(Enum):
    """Task execution status."""
    PENDING = "pending"
    RUNNING = "running"
    COMPLETED = "completed"
    FAILED = "failed"
    CANCELLED = "cancelled"
    RETRYING = "retrying"

class TaskExecutionError(Exception):
    """Exception raised when task execution fails."""
    pass

@dataclass
class WorkerPoolConfig:
    """Configuration for WorkerPool.

    Attributes:
        max_workers: Maximum number of concurrent workers (default: 50)
        task_timeout_seconds: Timeout for individual task execution (default: 180)
        max_retries: Maximum number of retries per task (default: 3)
        backoff_base_seconds: Base delay for exponential backoff (default: 1.0)
        backoff_max_seconds: Maximum backoff delay (default: 60.0)
        enable_instrumentation: Enable detailed logging and metrics (default: True)
    """
    max_workers: int = 50
    task_timeout_seconds: float = 180.0
    max_retries: int = 3
    backoff_base_seconds: float = 1.0
    backoff_max_seconds: float = 60.0
    enable_instrumentation: bool = True

@dataclass
class TaskMetrics:
    """Metrics for a single task execution.

    Attributes:
        task_id: Unique task identifier
        task_name: Human-readable task name
        status: Current task status
        start_time: Task start time (epoch seconds)
        end_time: Task end time (epoch seconds, None if not finished)
        execution_time_ms: Total execution time in milliseconds
        retries_used: Number of retries performed
        worker_id: ID of worker that executed the task
        error_message: Error message if task failed
    """
    task_id: str
    task_name: str
    status: TaskStatus
    start_time: float
    end_time: float | None = None
    execution_time_ms: float = 0.0
    retries_used: int = 0
    worker_id: str | None = None
    error_message: str | None = None

@dataclass
class TaskResult:
    """Result of a task execution.

    Attributes:
        task_id: Unique task identifier
        task_name: Human-readable task name
        success: Whether task succeeded
        result: Task result data (None if failed)
        error: Exception if task failed (None if succeeded)
        metrics: Execution metrics
    """
    task_id: str
    task_name: str
    success: bool
    result: Any = None
    error: Exception | None = None
    metrics: TaskMetrics | None = None

class WorkerPool:
    """
    Deterministic WorkerPool for parallel task execution.

    This pool provides controlled concurrency with the following guarantees:
    - No race conditions through thread-safe state management
    - Deterministic execution within priority groups
    - Proper resource cleanup and abort handling
    - Per-task instrumentation and logging

    Example:
        >>> config = WorkerPoolConfig(max_workers=10, max_retries=2)
        >>> pool = WorkerPool(config)
        >>>
        >>> def my_task(x):
        ...     return x * 2
        >>>
        >>> task_id = pool.submit_task("double_5", my_task, args=(5,))
        >>> results = pool.wait_for_all()
        >>> pool.shutdown()
    """

    def __init__(self, config: WorkerPoolConfig | None = None) -> None:
        """
        Initialize WorkerPool.

        Args:
            config: Pool configuration (uses defaults if None)
        """
        self.config = config or WorkerPoolConfig()
        self._executor: ThreadPoolExecutor | None = None
        self._futures: dict[str, Future] = {}
        self._task_info: dict[str, tuple[str, Callable, tuple, dict]] = {}
        self._metrics: dict[str, TaskMetrics] = {}
        self._lock = threading.Lock()
        self._abort_requested = threading.Event()
        self._is_shutdown = False

        logger.info(
            f"WorkerPool initialized: max_workers={self.config.max_workers}, "
            f"max_retries={self.config.max_retries}, "
            f"task_timeout={self.config.task_timeout_seconds}s"
        )

    def _create_executor(self) -> ThreadPoolExecutor:
        """Create thread pool executor lazily."""
        if self._executor is None:
            self._executor = ThreadPoolExecutor(
                max_workers=self.config.max_workers,
                thread_name_prefix="WorkerPool"
            )
        return self._executor

    def _calculate_backoff_delay(self, retry_count: int) -> float:
        """
        Calculate exponential backoff delay.

        Args:
            retry_count: Number of retries already attempted

        Returns:
            Delay in seconds, capped at backoff_max_seconds
        """
        delay = self.config.backoff_base_seconds * (2 ** retry_count)
        return min(delay, self.config.backoff_max_seconds)

    def _execute_task_with_retry(
        self,
        task_id: str,
        task_name: str,
        task_fn: Callable,
        args: tuple,
        kwargs: dict,
    ) -> Any:
        """
        Execute task with retry logic and exponential backoff.

        Args:
            task_id: Unique task identifier
            task_name: Human-readable task name
            task_fn: Task function to execute
            args: Positional arguments for task_fn
            kwargs: Keyword arguments for task_fn

        Returns:
            Task result

        Raises:
            TaskExecutionError: If task fails after all retries
        """
        worker_id = threading.current_thread().name
        retry_count = 0
        last_error = None

        # Initialize metrics
        with self._lock:
            self._metrics[task_id] = TaskMetrics(
                task_id=task_id,
                task_name=task_name,
                status=TaskStatus.RUNNING,
                start_time=time.time(),
                worker_id=worker_id
            )

        if self.config.enable_instrumentation:
            logger.info(f"[{task_id}] Starting task '{task_name}' on worker {worker_id}")

        while retry_count <= self.config.max_retries:
            # Check if abort was requested
            if self._abort_requested.is_set():
                with self._lock:
                    self._metrics[task_id].status = TaskStatus.CANCELLED
                    self._metrics[task_id].end_time = time.time()
                    self._metrics[task_id].execution_time_ms = (
                        (self._metrics[task_id].end_time -
self._metrics[task_id].start_time) * 1000
                    )

                if self.config.enable_instrumentation:
                    logger.warning(f"[{task_id}] Task '{task_name}' cancelled due to abort
 request")

                raise TaskExecutionError(f"Task {task_name} cancelled due to abort
request")

            try:
                # Execute task
                task_start = time.time()
                result = task_fn(*args, **kwargs)
                task_duration = (time.time() - task_start) * 1000

                # Update metrics on success
                with self._lock:
                    self._metrics[task_id].status = TaskStatus.COMPLETED
                    self._metrics[task_id].end_time = time.time()
                    self._metrics[task_id].execution_time_ms = task_duration
                    self._metrics[task_id].retries_used = retry_count

                if self.config.enable_instrumentation:
                    logger.info(
                        f"[{task_id}] Task '{task_name}' completed successfully "
                        f"in {task_duration:.2f}ms (retries: {retry_count})"
                    )

                return result

            except Exception as e:
                last_error = e

                # Update metrics on failure
                with self._lock:
                    self._metrics[task_id].retries_used = retry_count
                    self._metrics[task_id].error_message = str(e)

                if retry_count < self.config.max_retries:
                    # Calculate backoff delay
                    backoff_delay = self._calculate_backoff_delay(retry_count)

                    with self._lock:
                        self._metrics[task_id].status = TaskStatus.RETRYING

                    if self.config.enable_instrumentation:
                        logger.warning(
                            f"[{task_id}] Task '{task_name}' failed (attempt {retry_count
+ 1}), "
                            f"retrying after {backoff_delay:.2f}s: {e}"
                        )

                    # Wait before retrying (check abort periodically)
                    time.sleep(backoff_delay)
                    retry_count += 1
                else:
                    # All retries exhausted
                    with self._lock:
                        self._metrics[task_id].status = TaskStatus.FAILED
                        self._metrics[task_id].end_time = time.time()
                        self._metrics[task_id].execution_time_ms = (
                            (self._metrics[task_id].end_time -
self._metrics[task_id].start_time) * 1000
                        )

                    if self.config.enable_instrumentation:
                        logger.error(
                            f"[{task_id}] Task '{task_name}' failed after {retry_count}
retries: {e}"
                        )

                    raise TaskExecutionError(
                        f"Task {task_name} failed after {retry_count} retries:
{last_error}"
                    ) from last_error

            # Should not reach here, but just in case
            raise TaskExecutionError(f"Task {task_name} failed: {last_error}")

        def submit_task(
            self,
            task_name: str,
            task_fn: Callable,
            args: tuple = (),
            kwargs: dict[str, Any] | None = None,
        ) -> str:
            """
            Submit a task for execution.

            Args:
            task_name: Human-readable task name for logging
            task_fn: Callable to execute
            args: Positional arguments for task_fn
            kwargs: Keyword arguments for task_fn

            Returns:
            Unique task identifier

            Raises:
            RuntimeError: If pool is shutdown
            """
            if self._is_shutdown:
            raise RuntimeError("Cannot submit tasks to a shutdown WorkerPool")

            kwargs = kwargs or {}
            task_id = str(uuid4())

            with self._lock:
            # Store task info for potential retries
            self._task_info[task_id] = (task_name, task_fn, args, kwargs)

            # Submit task to executor
            executor = self._create_executor()
            future = executor.submit(
                self._execute_task_with_retry,
                task_id,
                task_name,
                task_fn,
                args,
                kwargs
            )
            self._futures[task_id] = future

            if self.config.enable_instrumentation:
            logger.debug(f"[{task_id}] Task '{task_name}' submitted to pool")

            return task_id

        def get_task_result(self, task_id: str, timeout: float | None = None) -> TaskResult:
            """
            Get result of a specific task.

            Args:
            task_id: Task identifier returned by submit_task
            timeout: Maximum time to wait for result in seconds (None = wait forever)
        Returns:
            TaskResult with execution metrics

        Raises:
            KeyError: If task_id is not found
            TimeoutError: If timeout is exceeded
        """
        with self._lock:
            if task_id not in self._futures:
                raise KeyError(f"Task {task_id} not found")

            future = self._futures[task_id]
            task_name = self._task_info[task_id][0]

        try:
            timeout_to_use = timeout or self.config.task_timeout_seconds
            result = future.result(timeout=timeout_to_use)

            with self._lock:
                metrics = self._metrics.get(task_id)

            return TaskResult(
                task_id=task_id,
                task_name=task_name,
                success=True,
                result=result,
                metrics=metrics
            )

        except TimeoutError as e:
            with self._lock:
                metrics = self._metrics.get(task_id)
                if metrics:
                    metrics.status = TaskStatus.FAILED
                    metrics.error_message = f"Timeout after {timeout_to_use}s"

            return TaskResult(
                task_id=task_id,
                task_name=task_name,
                success=False,
                error=e,
                metrics=metrics
            )

        except Exception as e:
            with self._lock:
                metrics = self._metrics.get(task_id)

            return TaskResult(
                task_id=task_id,
                task_name=task_name,
                success=False,
                error=e,
                metrics=metrics
            )

    def wait_for_all(
        self,
        timeout: float | None = None,
        return_when: str = "ALL_COMPLETED"
    ) -> list[TaskResult]:
        """
        Wait for all submitted tasks to complete.

        Args:
            timeout: Maximum time to wait in seconds (None = wait forever)
            return_when: When to return - "ALL_COMPLETED" or "FIRST_EXCEPTION"
        Returns:
            List of TaskResults for all tasks

        Raises:
            TimeoutError: If timeout is exceeded before all tasks complete
        """
        if self.config.enable_instrumentation:
            logger.info(f"Waiting for {len(self._futures)} tasks to complete...")

        start_time = time.time()
        results = []

        with self._lock:
            all_futures = list(self._futures.items())

        try:
            # Use as_completed for better progress tracking
            completed_count = 0
            for future in as_completed(
                [f for _, f in all_futures],
                timeout=timeout
            ):
                completed_count += 1

                # Find task_id for this future
                task_id = None
                with self._lock:
                    for tid, f in all_futures:
                        if f == future:
                            task_id = tid
                            break

                if task_id:
                    result = self.get_task_result(task_id, timeout=0.1)
                    results.append(result)

                    if self.config.enable_instrumentation and completed_count % 10 == 0:
                        elapsed = time.time() - start_time
                        logger.info(
                            f"Progress: {completed_count}/{len(all_futures)} tasks
completed "
                            f"({elapsed:.2f}s elapsed)"
                        )

                    # Check if we should return early on first exception
                    if return_when == "FIRST_EXCEPTION" and not result.success:
                        if self.config.enable_instrumentation:
                            logger.warning(
                                f"Returning early due to task failure: {result.task_name}"
                            )
                        break

            elapsed = time.time() - start_time
            if self.config.enable_instrumentation:
                successful = sum(1 for r in results if r.success)
                failed = sum(1 for r in results if not r.success)
                logger.info(
                    f"All tasks completed: {successful} succeeded, {failed} failed "
                    f"({elapsed:.2f}s total)"
                )

            return results

        except TimeoutError:
            elapsed = time.time() - start_time
            completed = len(results)
            pending = len(all_futures) - completed
            logger.error(
                f"Timeout after {elapsed:.2f}s: {completed} completed, {pending} pending"
            )

            # Get results for completed tasks
            for task_id, future in all_futures:
                if future.done() and task_id not in [r.task_id for r in results]:
                    try:
                        results.append(self.get_task_result(task_id, timeout=0.1))
                    except Exception as e:
                        logger.exception(f"Failed to get result for completed task
{task_id}: {e}")

            raise TimeoutError(
                f"Timeout waiting for tasks: {completed}/{len(all_futures)} completed"
            )

    def abort_pending_tasks(self) -> int:
        """
        Request abort of all pending tasks.

        This sets the abort flag, which will be checked by running tasks
        at their next safe point (before retry or next iteration).

        Returns:
            Number of tasks that were still pending
        """
        self._abort_requested.set()

        pending_count = 0
        with self._lock:
            for task_id, future in self._futures.items():
                if not future.done():
                    future.cancel()
                    pending_count += 1

                    # Update metrics
                    if task_id in self._metrics:
                        self._metrics[task_id].status = TaskStatus.CANCELLED

        if self.config.enable_instrumentation:
            logger.warning(f"Abort requested: {pending_count} tasks cancelled")

        return pending_count

    def get_metrics(self) -> dict[str, TaskMetrics]:
        """
        Get execution metrics for all tasks.

        Returns:
            Dictionary mapping task_id to TaskMetrics
        """
        with self._lock:
            return dict(self._metrics)

    def get_summary_metrics(self) -> dict[str, Any]:
        """
        Get summary metrics for the pool.

        Returns:
            Dictionary with aggregated metrics
        """
        with self._lock:
            metrics_list = list(self._metrics.values())

        if not metrics_list:
            return {
                "total_tasks": 0,
                "completed": 0,
                "failed": 0,
                "cancelled": 0,
                "running": 0,
                "pending": 0,
                "avg_execution_time_ms": 0.0,
                "total_retries": 0,
            }

        completed = sum(1 for m in metrics_list if m.status == TaskStatus.COMPLETED)
        failed = sum(1 for m in metrics_list if m.status == TaskStatus.FAILED)
        cancelled = sum(1 for m in metrics_list if m.status == TaskStatus.CANCELLED)
        running = sum(1 for m in metrics_list if m.status == TaskStatus.RUNNING)
        pending = sum(1 for m in metrics_list if m.status == TaskStatus.PENDING)

        completed_tasks = [m for m in metrics_list if m.status == TaskStatus.COMPLETED]
        avg_time = (
            sum(m.execution_time_ms for m in completed_tasks) / len(completed_tasks)
            if completed_tasks else 0.0
        )

        total_retries = sum(m.retries_used for m in metrics_list)

        return {
            "total_tasks": len(metrics_list),
            "completed": completed,
            "failed": failed,
            "cancelled": cancelled,
            "running": running,
            "pending": pending,
            "avg_execution_time_ms": avg_time,
            "total_retries": total_retries,
        }

    def shutdown(self, wait: bool = True, cancel_futures: bool = False) -> None:
        """
        Shutdown the worker pool.

        Args:
            wait: If True, wait for all tasks to complete before shutdown
            cancel_futures: If True, cancel all pending tasks
        """
        if self._is_shutdown:
            return

        if cancel_futures:
            self.abort_pending_tasks()

        if self._executor is not None:
            if self.config.enable_instrumentation:
                logger.info(f"Shutting down WorkerPool (wait={wait})")

            self._executor.shutdown(wait=wait, cancel_futures=cancel_futures)
            self._executor = None

        self._is_shutdown = True

        if self.config.enable_instrumentation:
            summary = self.get_summary_metrics()
            logger.info(
                f"WorkerPool shutdown complete. "
                f"Completed: {summary['completed']}, "
                f"Failed: {summary['failed']}, "
                f"Cancelled: {summary['cancelled']}"
            )

    def __enter__(self):
        """Context manager entry."""
        return self

    def __exit__(self, exc_type, exc_val, exc_tb):
        """Context manager exit."""
        self.shutdown(wait=True)
        return False

===== FILE: src/saaaaaa/config/__init__.py =====

===== FILE: src/saaaaaa/config/paths.py =====
"""
Centralized Path Configuration for F.A.R.F.A.N
================================================

This module provides a single source of truth for all filesystem paths
used throughout the project. This ensures:

1. Portability: Works in development and production
2. Configurability: Paths can be overridden via environment variables
3. Consistency: All modules use the same path definitions
4. Testability: Paths can be mocked for testing

Author: Python Pipeline Expert
Date: 2025-11-15

Usage:
    from saaaaaa.config.paths import DATA_DIR, OUTPUT_DIR, CACHE_DIR

    questionnaire = DATA_DIR / 'questionnaire_monolith.json'
    report = OUTPUT_DIR / 'analysis_report.json'
"""

import logging
import os
import sys
from pathlib import Path
from typing import Final, Tuple

# ============================================================================
# Project Root Detection
# ============================================================================

logger = logging.getLogger("saaaaaa.config.paths")


def _detect_project_root() -> Tuple[Path, str]:
    """
    Detect project root directory reliably in both dev and production.

    Strategy:
    1. If running from installed package: Use site-packages parent
    2. If running from source: Navigate from this file to project root
    3. Fallback: Use environment variable SAAAAAA_PROJECT_ROOT
    """
    # Check environment variable first (explicit override)
    if env_root := os.getenv('SAAAAAA_PROJECT_ROOT'):
        return Path(env_root).resolve(), "env"

    # Detect from this file's location
    # src/saaaaaa/config/paths.py → project_root
    this_file = Path(__file__).resolve()

    # Navigate up: paths.py -> config -> saaaaaa -> src -> project_root
    candidate = this_file.parents[3]

    # Verify this looks like our project (has setup.py or pyproject.toml)
    if (candidate / 'setup.py').exists() or (candidate / 'pyproject.toml').exists():
        return candidate, "markers"

    raise RuntimeError(
        "Unable to determine project root. "
        "Set the SAAAAAA_PROJECT_ROOT environment variable."
    )


# Project root (base for all other paths)
PROJECT_ROOT, PROJECT_ROOT_SOURCE = _detect_project_root()
logger.info("Project root detected via %s: %s", PROJECT_ROOT_SOURCE, PROJECT_ROOT)

# ============================================================================
# Core Directories
# ============================================================================

# Source code directory
SRC_DIR: Final[Path] = PROJECT_ROOT / 'src' / 'saaaaaa'

# Package root (for importlib.resources)
PACKAGE_ROOT: Final[Path] = SRC_DIR

# ============================================================================
# Data Directories (Configurable)
# ============================================================================

# Input data directory
DATA_DIR: Final[Path] = Path(
    os.getenv('SAAAAAA_DATA_DIR', str(PROJECT_ROOT / 'data'))
).resolve()

# Output directory for generated reports
OUTPUT_DIR: Final[Path] = Path(
    os.getenv('SAAAAAA_OUTPUT_DIR', str(PROJECT_ROOT / 'output'))
).resolve()

# Cache directory for temporary artifacts
CACHE_DIR: Final[Path] = Path(
    os.getenv('SAAAAAA_CACHE_DIR', str(PROJECT_ROOT / '.cache'))
).resolve()

# Logs directory
LOGS_DIR: Final[Path] = Path(
    os.getenv('SAAAAAA_LOGS_DIR', str(PROJECT_ROOT / 'logs'))
).resolve()

# ============================================================================
# Configuration Directories
# ============================================================================

# Configuration files directory
CONFIG_DIR: Final[Path] = SRC_DIR / 'config'

# Rules and schemas directory
RULES_DIR: Final[Path] = PROJECT_ROOT / 'config' / 'rules'
SCHEMAS_DIR: Final[Path] = PROJECT_ROOT / 'config' / 'schemas'

# ============================================================================
# Common Data Files
# ============================================================================

# Questionnaire monolith (canonical)
QUESTIONNAIRE_FILE: Final[Path] = DATA_DIR / 'questionnaire_monolith.json'

# Method catalog
METHOD_CATALOG_FILE: Final[Path] = DATA_DIR / 'metodos' / 'catalogo_metodos.json'

# ============================================================================
# Test Directories
# ============================================================================

# Test data directory (fixtures, golden files, etc.)
TEST_DATA_DIR: Final[Path] = PROJECT_ROOT / 'tests' / 'data'

# Test output directory (temporary outputs from tests)
TEST_OUTPUT_DIR: Final[Path] = PROJECT_ROOT / 'tests' / 'output'

# ============================================================================
# Utilities
# ============================================================================

def ensure_directories_exist() -> None:
    """
    Create all required directories if they don't exist.

    This should be called at application startup to ensure the
    filesystem is properly initialized.
    """
    required_dirs = [
        DATA_DIR,
        OUTPUT_DIR,
        CACHE_DIR,
        LOGS_DIR,
        TEST_OUTPUT_DIR,
    ]

    for dir_path in required_dirs:
        dir_path.mkdir(parents=True, exist_ok=True)


def get_output_path(plan_name: str, suffix: str = '') -> Path:
    """
    Get output path for a specific plan analysis.

    Args:
        plan_name: Name of the plan (e.g., "cpp_plan_1")
        suffix: Optional suffix for the output file

    Returns:
        Path to output file

    Example:
        >>> output_path = get_output_path("cpp_plan_1", "micro_analysis.json")
        >>> # Returns: output/cpp_plan_1/micro_analysis.json
    """
    plan_dir = OUTPUT_DIR / plan_name
    plan_dir.mkdir(parents=True, exist_ok=True)

    if suffix:
        return plan_dir / suffix
    return plan_dir


def get_cache_path(namespace: str, key: str) -> Path:
    """
    Get cache path for a specific namespace and key.

    Args:
        namespace: Cache namespace (e.g., "embeddings", "chunks")
        key: Cache key (will be sanitized)

    Returns:
        Path to cache file

    Example:
        >>> cache_path = get_cache_path("embeddings", "plan_123_chunk_5")
        >>> # Returns: .cache/embeddings/plan_123_chunk_5
    """
    namespace_dir = CACHE_DIR / namespace
    namespace_dir.mkdir(parents=True, exist_ok=True)

    # Sanitize key (remove dangerous characters)
    safe_key = key.replace('/', '_').replace('\\', '_').replace('..', '_')

    return namespace_dir / safe_key


def validate_paths() -> bool:
    """
    Validate that all critical paths exist and are accessible.

    Returns:
        True if all paths are valid, False otherwise
    """
    issues = []

    # Check PROJECT_ROOT
    if not PROJECT_ROOT.exists():
        issues.append(f"PROJECT_ROOT does not exist: {PROJECT_ROOT}")

    # Check SRC_DIR
    if not SRC_DIR.exists():
        issues.append(f"SRC_DIR does not exist: {SRC_DIR}")

    # Check critical data files
    if not QUESTIONNAIRE_FILE.exists():
        issues.append(f"Questionnaire file not found: {QUESTIONNAIRE_FILE}")

    if issues:
        print("⚠   Path validation issues:", file=sys.stderr)
        for issue in issues:
            print(f"   - {issue}", file=sys.stderr)
        return False

    return True


# ============================================================================
# Initialization
# ============================================================================

# Ensure directories exist on import (safe, idempotent)
ensure_directories_exist()

# ============================================================================
# Compatibility Shims (DEPRECATED - for migration period)
# ============================================================================

# These provide backward compatibility during migration
# TODO: Remove these after migration is complete

def proj_root() -> Path:
    """DEPRECATED: Use PROJECT_ROOT instead."""
    import warnings
    warnings.warn(
        "proj_root() is deprecated. Use PROJECT_ROOT constant instead.",
        DeprecationWarning,
        stacklevel=2
    )
    return PROJECT_ROOT


def reports_dir() -> Path:
    """DEPRECATED: Use OUTPUT_DIR instead."""
    import warnings
    warnings.warn(
        "reports_dir() is deprecated. Use OUTPUT_DIR constant instead.",
        DeprecationWarning,
        stacklevel=2
    )
    return OUTPUT_DIR


# ============================================================================
# Debug Information
# ============================================================================

if __name__ == "__main__":
    """Print path configuration for debugging."""
    print("=" * 80)
    print("F.A.R.F.A.N Path Configuration")
    print("=" * 80)
    print()
    print(f"PROJECT_ROOT:     {PROJECT_ROOT}")
    print(f"SRC_DIR:          {SRC_DIR}")
    print(f"DATA_DIR:         {DATA_DIR}")
    print(f"OUTPUT_DIR:       {OUTPUT_DIR}")
    print(f"CACHE_DIR:        {CACHE_DIR}")
    print(f"LOGS_DIR:         {LOGS_DIR}")
    print()
    print(f"QUESTIONNAIRE:    {QUESTIONNAIRE_FILE}")
    print(f"  Exists: {QUESTIONNAIRE_FILE.exists()}")
    print()
    print("Validation:", "✓ PASS" if validate_paths() else "✗ FAIL")
    print()

===== FILE: src/saaaaaa/contracts.py =====
"""Contracts module re-exports from utils.contracts package.

This module provides backward compatibility for code that imports
contracts from saaaaaa.contracts instead of saaaaaa.utils.contracts.
"""

from saaaaaa.utils.contracts import (
    MISSING,
    AnalysisInputV1,
    AnalysisInputV1Optional,
    AnalysisOutputV1,
    AnalysisOutputV1Optional,
    AnalyzerProtocol,
    ContractMismatchError,
    DocumentLoaderProtocol,
    DocumentMetadataV1,
    DocumentMetadataV1Optional,
    ExecutionContextV1,
    ExecutionContextV1Optional,
    ProcessedTextV1,
    ProcessedTextV1Optional,
    SentenceCollection,
    TextDocument,
    TextProcessorProtocol,
    ensure_hashable,
    ensure_iterable_not_string,
    validate_contract,
    validate_mapping_keys,
)

__all__ = [
    "MISSING",
    "AnalysisInputV1",
    "AnalysisInputV1Optional",
    "AnalysisOutputV1",
    "AnalysisOutputV1Optional",
    "AnalyzerProtocol",
    "ContractMismatchError",
    "DocumentLoaderProtocol",
    "DocumentMetadataV1",
    "DocumentMetadataV1Optional",
    "ExecutionContextV1",
    "ExecutionContextV1Optional",
    "ProcessedTextV1",
    "ProcessedTextV1Optional",
    "SentenceCollection",
    "TextDocument",
    "TextProcessorProtocol",
    "ensure_hashable",
    "ensure_iterable_not_string",
    "validate_contract",
    "validate_mapping_keys",
]

===== FILE: src/saaaaaa/controls/__init__.py =====
"""Controls module for system validation and checks."""

===== FILE: src/saaaaaa/controls/graphs/__init__.py =====
"""Graph-based controls and analysis."""

===== FILE: src/saaaaaa/core/__init__.py =====
"""Core components of the SAAAAAA system."""

===== FILE: src/saaaaaa/core/aggregation.py =====
"""Aggregation module re-exports from processing package.

This module provides backward compatibility for code that imports
aggregation classes from saaaaaa.core.aggregation instead of
saaaaaa.processing.aggregation.
"""

from saaaaaa.processing.aggregation import (
    AreaPolicyAggregator,
    AreaScore,
    ClusterAggregator,
    ClusterScore,
    DimensionAggregator,
    DimensionScore,
    MacroAggregator,
    ScoredResult,
)

__all__ = [
    "AreaPolicyAggregator",
    "AreaScore",
    "ClusterAggregator",
    "ClusterScore",
    "DimensionAggregator",
    "DimensionScore",
    "MacroAggregator",
    "ScoredResult",
]

===== FILE: src/saaaaaa/core/boot_checks.py =====
"""
Boot-time validation checks for F.A.R.F.A.N runtime dependencies.

This module provides boot checks that validate critical dependencies before
pipeline execution. In PROD mode, failures abort execution unless explicitly
allowed by configuration flags.
"""

import importlib
import json
from pathlib import Path
from typing import Optional

from saaaaaa.core.runtime_config import RuntimeConfig, RuntimeMode


class BootCheckError(Exception):
    """
    Raised when a boot check fails in strict mode.

    Attributes:
        component: Component that failed (e.g., "contradiction_module")
        reason: Human-readable failure reason
        code: Machine-readable error code
    """

    def __init__(self, component: str, reason: str, code: str):
        self.component = component
        self.reason = reason
        self.code = code
        super().__init__(f"Boot check failed [{code}] {component}: {reason}")


def check_contradiction_module_available(config: RuntimeConfig) -> bool:
    """
    Check if contradiction detection module is available.

    Args:
        config: Runtime configuration

    Returns:
        True if module available or fallback allowed

    Raises:
        BootCheckError: If module unavailable in strict PROD mode
    """
    try:
        from saaaaaa.analysis.contradiction_detection import PolicyContradictionDetector
        return True
    except ImportError as e:
        if config.mode == RuntimeMode.PROD and not config.allow_contradiction_fallback:
            raise BootCheckError(
                component="contradiction_module",
                reason=f"PolicyContradictionDetector not available: {e}",
                code="CONTRADICTION_MODULE_MISSING"
            )
        # Fallback allowed in DEV/EXPLORATORY or with flag
        return False


def check_wiring_validator_available(config: RuntimeConfig) -> bool:
    """
    Check if WiringValidator is available.

    Args:
        config: Runtime configuration

    Returns:
        True if validator available or disable allowed

    Raises:
        BootCheckError: If validator unavailable in strict PROD mode
    """
    try:
        from saaaaaa.core.wiring.validator import WiringValidator
        return True
    except ImportError as e:
        if config.mode == RuntimeMode.PROD and not config.allow_validator_disable:
            raise BootCheckError(
                component="wiring_validator",
                reason=f"WiringValidator not available: {e}",
                code="WIRING_VALIDATOR_MISSING"
            )
        return False


def check_spacy_model_available(model_name: str, config: RuntimeConfig) -> bool:
    """
    Check if preferred spaCy model is installed.

    Args:
        model_name: spaCy model name (e.g., "es_core_news_lg")
        config: Runtime configuration

    Returns:
        True if model available

    Raises:
        BootCheckError: If model unavailable in PROD mode
    """
    try:
        import spacy
        spacy.load(model_name)
        return True
    except (ImportError, OSError) as e:
        if config.mode == RuntimeMode.PROD:
            raise BootCheckError(
                component="spacy_model",
                reason=f"spaCy model '{model_name}' not available: {e}",
                code="SPACY_MODEL_MISSING"
            )
        return False


def check_calibration_files(config: RuntimeConfig, calibration_dir: Optional[Path] = None)
 -> bool:
    """
    Check calibration files exist and have required structure.

    Args:
        config: Runtime configuration
        calibration_dir: Directory containing calibration files (default:
config/layer_calibrations)

    Returns:
        True if calibration files valid

    Raises:
        BootCheckError: If calibration invalid in strict PROD mode
    """
    if calibration_dir is None:
        calibration_dir = Path("config/layer_calibrations")

    if not calibration_dir.exists():
        if config.mode == RuntimeMode.PROD and config.strict_calibration:
            raise BootCheckError(
                component="calibration_files",
                reason=f"Calibration directory not found: {calibration_dir}",
                code="CALIBRATION_DIR_MISSING"
            )
        return False

    # Check for required calibration files
    required_files = ["intrinsic_calibration.json", "fusion_specification.json"]
    missing_files = []
    for filename in required_files:
        file_path = calibration_dir.parent / filename
        if not file_path.exists():
            missing_files.append(filename)

    if missing_files:
        if config.mode == RuntimeMode.PROD and config.strict_calibration:
            raise BootCheckError(
                component="calibration_files",
                reason=f"Missing required calibration files: {', '.join(missing_files)}",
                code="CALIBRATION_FILES_MISSING"
            )
        return False

    # Validate _base_weights presence in strict mode
    if config.strict_calibration:
        intrinsic_path = calibration_dir.parent / "intrinsic_calibration.json"
        try:
            with open(intrinsic_path) as f:
                data = json.load(f)

            if "_base_weights" not in data:
                if config.mode == RuntimeMode.PROD:
                    raise BootCheckError(
                        component="calibration_files",
                        reason=f"Missing _base_weights in {intrinsic_path}",
                        code="CALIBRATION_BASE_WEIGHTS_MISSING"
                    )
                return False
        except (json.JSONDecodeError, IOError) as e:
            if config.mode == RuntimeMode.PROD:
                raise BootCheckError(
                    component="calibration_files",
                    reason=f"Failed to parse {intrinsic_path}: {e}",
                    code="CALIBRATION_PARSE_ERROR"
                )
            return False

    return True


def check_orchestration_metrics_contract(config: RuntimeConfig) -> bool:
    """
    Check that orchestration metrics contract is properly defined.

    This validates that the _execution_metrics['phase_2'] schema exists
    and is properly structured.

    Args:
        config: Runtime configuration

    Returns:
        True if contract valid

    Raises:
        BootCheckError: If contract invalid in PROD mode
    """
    try:
        # Import orchestrator to check metrics contract
        from saaaaaa.core.orchestrator.core import Orchestrator

        # Verify phase_2 metrics schema exists
        # This is a placeholder - actual implementation would check the schema
        return True
    except ImportError as e:
        if config.mode == RuntimeMode.PROD:
            raise BootCheckError(
                component="orchestration_metrics",
                reason=f"Orchestrator not available: {e}",
                code="ORCHESTRATOR_MISSING"
            )
        return False


def check_networkx_available() -> bool:
    """
    Check if NetworkX is available for graph metrics.

    Returns:
        True if NetworkX available

    Note:
        This is a soft check - NetworkX unavailability is Category B (quality degradation)
    """
    try:
        import networkx
        return True
    except ImportError:
        return False


def run_boot_checks(config: RuntimeConfig) -> dict[str, bool]:
    """
    Run all boot checks and return results.

    Args:
        config: Runtime configuration

    Returns:
        Dictionary mapping check name to success status

    Raises:
        BootCheckError: If any critical check fails in strict PROD mode

    Example:
        >>> config = RuntimeConfig.from_env()
        >>> results = run_boot_checks(config)
        >>> assert results['contradiction_module']
    """
    results = {}

    # Critical checks (Category A)
    results['contradiction_module'] = check_contradiction_module_available(config)
    results['wiring_validator'] = check_wiring_validator_available(config)
    results['spacy_model'] = check_spacy_model_available(config.preferred_spacy_model,
config)
    results['calibration_files'] = check_calibration_files(config)
    results['orchestration_metrics'] = check_orchestration_metrics_contract(config)

    # Quality checks (Category B)
    results['networkx'] = check_networkx_available()

    return results


def get_boot_check_summary(results: dict[str, bool]) -> str:
    """
    Generate human-readable summary of boot check results.

    Args:
        results: Boot check results from run_boot_checks()

    Returns:
        Formatted summary string
    """
    passed = sum(1 for v in results.values() if v)
    total = len(results)

    lines = [f"Boot Checks: {passed}/{total} passed"]
    lines.append("")

    for check, success in results.items():
        status = "✓" if success else "✗"
        lines.append(f"  {status} {check}")

    return "\n".join(lines)

===== FILE: src/saaaaaa/core/calibration/__init__.py =====
"""
SAAAAAA Calibration System.

This package implements the 7-layer method calibration framework:
- @b (Base): Intrinsic method quality
- @u (Unit): PDT quality
- @q, @d, @p (Contextual): Method-context compatibility
- @C (Congruence): Method ensemble validation
- @chain (Chain): Data flow integrity
- @m (Meta): Governance and observability

Final scores are produced via Choquet 2-Additive aggregation.
"""

from .base_layer import BaseLayerEvaluator
from .chain_layer import ChainLayerEvaluator
from .choquet_aggregator import ChoquetAggregator
from .compatibility import (
    CompatibilityRegistry,
    ContextualLayerEvaluator,
)
from .config import (
    DEFAULT_CALIBRATION_CONFIG,
    CalibrationSystemConfig,
    ChoquetAggregationConfig,
    MetaLayerConfig,
    UnitLayerConfig,
)
from .congruence_layer import CongruenceLayerEvaluator
from .data_structures import (
    CalibrationResult,
    CalibrationSubject,
    CompatibilityMapping,
    ContextTuple,
    InteractionTerm,
    LayerID,
    LayerScore,
)
from .meta_layer import MetaLayerEvaluator
from .orchestrator import CalibrationOrchestrator
from .pdt_structure import PDTStructure
from .validator import (
    CalibrationValidator,
    ValidationDecision,
    ValidationResult,
    ValidationReport,
    FailureReason,
)

# Import protocols for type checking
from .protocols import (
    BaseLayerEvaluatorProtocol,
    ChainLayerEvaluatorProtocol,
    CongruenceLayerEvaluatorProtocol,
    ContextualLayerEvaluatorProtocol,
    LayerEvaluator,
    MetaLayerEvaluatorProtocol,
    UnitLayerEvaluatorProtocol,
    validate_evaluator_protocol,
)
from .unit_layer import UnitLayerEvaluator

__all__ = [
    # Data structures
    "LayerID",
    "LayerScore",
    "ContextTuple",
    "CalibrationSubject",
    "CompatibilityMapping",
    "InteractionTerm",
    "CalibrationResult",
    "PDTStructure",
    # Configuration
    "UnitLayerConfig",
    "MetaLayerConfig",
    "ChoquetAggregationConfig",
    "CalibrationSystemConfig",
    "DEFAULT_CALIBRATION_CONFIG",
    # Layer Evaluators
    "BaseLayerEvaluator",
    "UnitLayerEvaluator",
    "CompatibilityRegistry",
    "ContextualLayerEvaluator",
    "CongruenceLayerEvaluator",
    "ChainLayerEvaluator",
    "MetaLayerEvaluator",
    # Aggregation & Orchestration
    "ChoquetAggregator",
    "CalibrationOrchestrator",
    # Validation
    "CalibrationValidator",
    "ValidationDecision",
    "ValidationResult",
    "ValidationReport",
    "FailureReason",
    # Protocols
    "LayerEvaluator",
    "BaseLayerEvaluatorProtocol",
    "UnitLayerEvaluatorProtocol",
    "ContextualLayerEvaluatorProtocol",
    "CongruenceLayerEvaluatorProtocol",
    "ChainLayerEvaluatorProtocol",
    "MetaLayerEvaluatorProtocol",
    "validate_evaluator_protocol",
]

===== FILE: src/saaaaaa/core/calibration/base_layer.py =====
"""
Base Layer (@b) - Intrinsic Quality Evaluator.

This layer evaluates the inherent quality of methods based on:
- b_theory: Theoretical foundation quality
- b_impl: Implementation quality
- b_deploy: Deployment maturity

Scores are loaded from intrinsic_calibration.json, which is populated
by rigorous_calibration_triage.py using intrinsic_calibration_rubric.json.
"""
import json
import logging
from pathlib import Path
from typing import Any, Optional
from .data_structures import LayerID, LayerScore

logger = logging.getLogger(__name__)


class BaseLayerEvaluator:
    """
    Evaluates Base Layer (@b) - Intrinsic method quality.

    This layer reads pre-computed calibration scores from the
    intrinsic calibration registry.

    Usage:
        evaluator = BaseLayerEvaluator("config/intrinsic_calibration.json")
        score = evaluator.evaluate("pattern_extractor_v2")
    """

    # Default weights (used if not in JSON) - FALLBACK ONLY
    DEFAULT_THEORY_WEIGHT = 0.4
    DEFAULT_IMPL_WEIGHT = 0.35
    DEFAULT_DEPLOY_WEIGHT = 0.25

    def __init__(
        self,
        intrinsic_calibration_path: Path | str,
        parameter_loader: Optional[Any] = None
    ) -> None:
        """
        Initialize evaluator with intrinsic calibration data.

        Args:
            intrinsic_calibration_path: Path to intrinsic_calibration.json
            parameter_loader: Optional MethodParameterLoader for loading thresholds

        Raises:
            FileNotFoundError: If calibration file doesn't exist
            ValueError: If calibration file has invalid structure
        """
        self.calibration_path = Path(intrinsic_calibration_path)
        self.calibrations: dict[str, dict[str, Any]] = {}

        # These will be loaded from JSON (or use defaults)
        self.theory_weight: float = self.DEFAULT_THEORY_WEIGHT
        self.impl_weight: float = self.DEFAULT_IMPL_WEIGHT
        self.deploy_weight: float = self.DEFAULT_DEPLOY_WEIGHT

        # ZERO TOLERANCE: Load thresholds and penalties from JSON
        try:
            from .config_loaders import ThresholdLoader, PenaltyLoader

            threshold_loader = ThresholdLoader.get_instance()
            penalty_loader = PenaltyLoader.get_instance()

            # Load quality thresholds from JSON
            base_thresholds = threshold_loader.get_base_layer_quality_thresholds()
            self.excellent_threshold = base_thresholds["excellent"]
            self.good_threshold = base_thresholds["good"]
            self.acceptable_threshold = base_thresholds["acceptable"]

            # Load uncalibrated penalty from JSON
            self.uncalibrated_penalty =
penalty_loader.get_base_layer_penalty("uncalibrated_method")

            logger.info(
                "base_layer_config_loaded_from_json",
                extra={
                    "excellent_threshold": self.excellent_threshold,
                    "good_threshold": self.good_threshold,
                    "acceptable_threshold": self.acceptable_threshold,
                    "uncalibrated_penalty": self.uncalibrated_penalty
                }
            )
        except Exception as e:
            logger.error(
                "failed_to_load_base_layer_config_from_json",
                extra={"error": str(e)}
            )
            raise ValueError(
                f"ZERO TOLERANCE VIOLATION: Failed to load base layer config from JSON.\n"
                f"All values MUST be in JSON files, not hardcoded.\n"
                f"Error: {e}"
            )

        self._load()

        # Verify aggregation weights sum to 1.0
        total_weight = self.theory_weight + self.impl_weight + self.deploy_weight
        if abs(total_weight - 1.0) > 1e-6:
            raise ValueError(
                f"Base layer component weights must sum to 1.0, got {total_weight}"
            )

    def _load(self) -> None:
        """Load intrinsic calibration scores and weights from JSON."""
        if not self.calibration_path.exists():
            raise FileNotFoundError(
                f"Intrinsic calibration file not found: {self.calibration_path}\n"
                f"Run scripts/rigorous_calibration_triage.py to generate it."
            )

        with open(self.calibration_path, encoding='utf-8') as f:
            data = json.load(f)

        # Validate structure
        if "methods" not in data:
            raise ValueError(
                "Intrinsic calibration file must have 'methods' key at top level"
            )

        # Load weights from JSON if available
        if "_base_weights" in data:
            base_weights = data["_base_weights"]
            self.theory_weight = float(base_weights.get("w_th",
self.DEFAULT_THEORY_WEIGHT))
            self.impl_weight = float(base_weights.get("w_imp", self.DEFAULT_IMPL_WEIGHT))
            self.deploy_weight = float(base_weights.get("w_dep",
self.DEFAULT_DEPLOY_WEIGHT))

            logger.info(
                "base_layer_weights_loaded",
                extra={
                    "theory_weight": self.theory_weight,
                    "impl_weight": self.impl_weight,
                    "deploy_weight": self.deploy_weight,
                    "source": "intrinsic_calibration.json"
                }
            )
        else:
            logger.info(
                "base_layer_weights_using_defaults",
                extra={
                    "theory_weight": self.theory_weight,
                    "impl_weight": self.impl_weight,
                    "deploy_weight": self.deploy_weight
                }
            )
        # Load each method's calibration
        methods = data["methods"]

        for method_id, cal_data in methods.items():
            # Skip metadata entries (start with _)
            if method_id.startswith("_"):
                continue

            calibration_status = cal_data.get("calibration_status", "unknown")

            # Only load methods with computed calibration
            if calibration_status == "computed":
                self.calibrations[method_id] = {
                    "b_theory": cal_data.get("b_theory", 0.0),
                    "b_impl": cal_data.get("b_impl", 0.0),
                    "b_deploy": cal_data.get("b_deploy", 0.0),
                    "evidence": cal_data.get("evidence", {}),
                    "layer": cal_data.get("layer", "unknown"),
                    "last_updated": cal_data.get("last_updated", "unknown"),
                }

                logger.debug(
                    "intrinsic_calibration_loaded",
                    extra={
                        "method": method_id,
                        "b_theory": self.calibrations[method_id]["b_theory"],
                        "b_impl": self.calibrations[method_id]["b_impl"],
                        "b_deploy": self.calibrations[method_id]["b_deploy"],
                    }
                )
            elif calibration_status == "excluded":
                # Methods explicitly excluded from calibration
                logger.debug(
                    "method_excluded_from_calibration",
                    extra={
                        "method": method_id,
                        "reason": cal_data.get("reason", "unknown"),
                    }
                )

        logger.info(
            "base_layer_calibrations_loaded",
            extra={
                "total_methods": len(self.calibrations),
                "calibration_file": str(self.calibration_path),
            }
        )

    def evaluate(self, method_id: str) -> LayerScore:
        """
        Evaluate BASE layer (@b) for a method.

        This retrieves pre-computed intrinsic calibration scores and
        aggregates them using configured weights.

        Args:
            method_id: Canonical method identifier (e.g., "pattern_extractor_v2")

        Returns:
            LayerScore with @b score and component breakdown

        Formula:
            @b = w_theory · b_theory + w_impl · b_impl + w_deploy · b_deploy
            where w_theory=0.4, w_impl=0.35, w_deploy=0.25
        """
        # Check if method has calibration data
        if method_id not in self.calibrations:
            logger.warning(
                "method_not_calibrated",
                extra={
                    "method": method_id,
                    "penalty_score": self.uncalibrated_penalty,
                }
            )
            return LayerScore(
                layer=LayerID.BASE,
                score=self.uncalibrated_penalty,
                rationale=f"Method '{method_id}' not found in intrinsic calibration
registry. "
                         f"Using penalty score {self.uncalibrated_penalty} (loaded from
JSON). "
                         f"Run rigorous_calibration_triage.py to calibrate.",
                metadata={
                    "calibration_status": "not_found",
                    "penalty": True,
                }
            )

        # Get calibration components
        cal = self.calibrations[method_id]
        b_theory = cal["b_theory"]
        b_impl = cal["b_impl"]
        b_deploy = cal["b_deploy"]

        # Aggregate components using weights
        base_score = (
            self.theory_weight * b_theory +
            self.impl_weight * b_impl +
            self.deploy_weight * b_deploy
        )

        # Determine quality level using configurable thresholds
        if base_score >= self.excellent_threshold:
            quality = "excellent"
        elif base_score >= self.good_threshold:
            quality = "good"
        elif base_score >= self.acceptable_threshold:
            quality = "acceptable"
        else:
            quality = "needs_improvement"

        logger.info(
            "base_layer_evaluated",
            extra={
                "method": method_id,
                "base_score": base_score,
                "quality": quality,
                "b_theory": b_theory,
                "b_impl": b_impl,
                "b_deploy": b_deploy,
            }
        )

        # Create LayerScore with full breakdown
        return LayerScore(
            layer=LayerID.BASE,
            score=base_score,
            components={
                "b_theory": b_theory,
                "b_impl": b_impl,
                "b_deploy": b_deploy,
                "theory_weight": self.theory_weight,
                "impl_weight": self.impl_weight,
                "deploy_weight": self.deploy_weight,
            },
            rationale=f"Intrinsic quality: {quality} "
                      f"(theory={b_theory:.2f}, impl={b_impl:.2f}, deploy={b_deploy:.2f})",
            metadata={
                "calibration_status": "loaded",
                "layer": cal["layer"],
                "last_updated": cal["last_updated"],
                "formula": f"{self.theory_weight}*theory + {self.impl_weight}*impl +
{self.deploy_weight}*deploy",
                "quality_level": quality,
            }
        )

    def get_calibration_info(self, method_id: str) -> dict[str, Any] | None:
        """
        Get full calibration info for a method (including evidence).

        This is useful for debugging or detailed auditing.

        Args:
            method_id: Method identifier

        Returns:
            Calibration dictionary or None if not found
        """
        return self.calibrations.get(method_id)

    def get_coverage_stats(self) -> dict[str, Any]:
        """
        Get statistics about calibration coverage.

        Returns:
            Dict with coverage information:
                - total_calibrated: Number of methods with calibration
                - by_layer: Breakdown by layer
                - avg_scores: Average scores per component
        """
        total = len(self.calibrations)

        # Count by layer
        by_layer: dict[str, int] = {}
        for cal in self.calibrations.values():
            layer = cal["layer"]
            by_layer[layer] = by_layer.get(layer, 0) + 1

        # Compute average scores
        if total > 0:
            avg_theory = sum(c["b_theory"] for c in self.calibrations.values()) / total
            avg_impl = sum(c["b_impl"] for c in self.calibrations.values()) / total
            avg_deploy = sum(c["b_deploy"] for c in self.calibrations.values()) / total
        else:
            avg_theory = avg_impl = avg_deploy = 0.0

        return {
            "total_calibrated": total,
            "by_layer": by_layer,
            "avg_scores": {
                "b_theory": round(avg_theory, 3),
                "b_impl": round(avg_impl, 3),
                "b_deploy": round(avg_deploy, 3),
            },
            "calibration_file": str(self.calibration_path),
        }

===== FILE: src/saaaaaa/core/calibration/chain_layer.py =====
"""
Chain Layer (@chain) - Full Implementation.

Validates data flow integrity for method chains.
```

```
Discrete scoring system: {1.0, 0.8, 0.6, 0.3, 0.0}
"""
import logging
from typing import Any

logger = logging.getLogger(__name__)


class ChainLayerEvaluator:
    """
    Validates chain integrity for method execution.

    Attributes:
        signatures: Dictionary mapping method IDs to their input/output signatures
    """

    def __init__(self, method_signatures: dict[str, Any]) -> None:
        """
        Initialize evaluator with method signatures.

        Args:
            method_signatures: Dict with method input/output signatures
        """
        self.signatures = method_signatures
        logger.info("chain_evaluator_initialized", extra={"num_methods":
len(method_signatures)})

    def evaluate(
        self,
        method_id: str,
        provided_inputs: list[str],
        upstream_outputs: dict[str, str] = None
    ) -> float:
        """
        Validate chain integrity for a method.

        Discrete scoring: {1.0, 0.8, 0.6, 0.3, 0.0}

        Args:
            method_id: Method to validate
            provided_inputs: Inputs being provided
            upstream_outputs: Types from upstream (for type checking)

        Returns:
            Chain score ∈ {0.0, 0.3, 0.6, 0.8, 1.0}
        """
        if method_id not in self.signatures:
            logger.warning("method_signature_missing", extra={"method": method_id})
            return 0.0  # Undeclared method

        sig = self.signatures[method_id]
        required = set(sig.get("required_inputs", []))
        optional = set(sig.get("optional_inputs", []))
        critical_optional = set(sig.get("critical_optional", []))
        provided = set(provided_inputs)

        logger.info(
            "chain_validation_start",
            extra={
                "method": method_id,
                "required": list(required),
                "provided": list(provided)
            }
        )

        # Check 1: Required inputs (HARD FAILURE if missing)
        missing_required = required - provided
        if missing_required:
            logger.error(
                "chain_hard_mismatch",
                extra={
                    "method": method_id,
                    "missing_required": list(missing_required)
                }
            )
            return 0.0  # Hard mismatch

        # Check 2: Critical optional inputs
        missing_critical = critical_optional - provided
        if missing_critical:
            logger.warning(
                "chain_missing_critical_optional",
                extra={
                    "method": method_id,
                    "missing": list(missing_critical)
                }
            )
            return 0.3  # Missing critical optional

        # Check 3: Regular optional inputs
        missing_optional = (optional - critical_optional) - provided
        if missing_optional:
            logger.info(
                "chain_missing_optional",
                extra={
                    "method": method_id,
                    "missing": list(missing_optional)
                }
            )
            # Check severity: if many missing, lower score
            optional_count = len(optional - critical_optional)
            missing_count = len(missing_optional)
            if optional_count > 0:
                ratio = missing_count / optional_count
                if ratio > 0.5:
                    return 0.6  # Many optional missing
                else:
                    return 0.8  # Some optional missing

        # All inputs present
        logger.info("chain_valid", extra={"method": method_id, "score": 1.0})
        return 1.0

    def validate_chain_sequence(
        self,
        method_sequence: list[str],
        initial_inputs: list[str]
    ) -> dict[str, float]:
        """
        Validate entire chain of methods.

        Args:
            method_sequence: Ordered list of methods
            initial_inputs: Inputs available at start

        Returns:
            Dict mapping method_id to chain score
        """
        results = {}
        available_inputs = set(initial_inputs)

        for method_id in method_sequence:
            # Validate this method
            score = self.evaluate(method_id, list(available_inputs))
            results[method_id] = score
        # Add this method's output to available inputs
        # (simplified - assumes output name matches method)
        available_inputs.add(f"{method_id}_output")

    return results

def compute_chain_quality(
    self,
    method_scores: dict[str, float]
) -> float:
    """
    Compute overall chain quality.

    Formula: Minimum score in chain (weakest link)

    Returns:
        Overall quality ∈ [0.0, 1.0]
    """
    if not method_scores:
        return 0.0
```