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SEMESTER PROJECT - DATA SCIENCE

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Scaling and Improving ProVe for  
Large-Scale Wikidata Provenance  
Verification:  
A Reproducibility Audit and Forensic  
Restoration

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## Abstract

Wikidata serves as a critical backend for the semantic web, supplying structured information to applications ranging from search engines to virtual assistants. As a secondary knowledge source, its reliability depends entirely on verifiable references. With over one billion claims requiring validation, manual verification is prohibitively expensive.

This project began as an effort to scale **ProVe**, an automated pipeline for Knowledge Graph (KG) triple verification against textual sources. However, initial forensic auditing revealed a critical **Reproducibility Crisis**: the models provided in the public repository exhibited severe performance degradation compared to the original “Black Box” API, which operates at 87.5% accuracy. The project pivoted from performance benchmarking to **Root Cause Analysis** and **Forensic Reconstruction**.

The investigation identified a **17.5% performance gap** between the API and locally reproducible models. While I achieved **PARITY** in the Verbalization module through T5 fine-tuning on WebNLG 2020, the Retrieval and Verification modules remained in a state of **GAP**. Consequently, I made a deliberate methodological decision to bypass quantitative metrics for underperforming modules, prioritizing intellectual honesty over misleading performance statistics.

This report documents the forensic reconstruction of the pipeline, the discovery of the “Modernization Trap” (where state-of-the-art Dense Retrieval underperforms legacy keyword heuristics), and qualitative evidence of the **Provenance vs. Truth** gap through case studies including the “Ciobama” vandalism trap and Kenyan citizenship confusion. I demonstrate that successful reproduction was achieved only for Module 1, while the remaining gaps serve as a critique of current reproducibility standards in AI research.

# 1 Introduction

## 1.1 The Reproducibility Crisis in Automated Verification

The reliability of Knowledge Graphs depends on the citation of authoritative sources. In Wikidata, a statement such as (*Barack Obama, place of birth, Honolulu*) includes a reference URL, yet the mere existence of a URL does not guarantee that the source supports the claim. The source may be outdated, irrelevant, or contradictory.

The **ProVe** pipeline was proposed to automate this verification process [1] using Natural Language Processing (NLP). However, initial investigation revealed a stark discrepancy: while the original ProVe API operates as a high-functioning “Black Box” (87.5% accuracy), the models provided in the public repository (via SharePoint) exhibit severe performance degradation.

This discovery necessitated a full **Forensic Reconstruction** of the local pipeline and a pivot from performance optimization to **Root Cause Analysis**. Rather than publishing incomplete metrics that would mask these fundamental disparities, I prioritized understanding the gap’s origins over generating misleading performance statistics.

## 1.2 Project Pivot: From Scaling to Audit

The project underwent a critical evolution:

1. **Initial Objective:** Scale the ProVe pipeline for large-scale Wikidata auditing.
2. **Discovery Phase:** Baseline testing revealed the API-repository performance gap.
3. **Pivot Decision:** Shift focus to Reconstruction and Root Cause Analysis.
4. **Intellectual Honesty:** Deliberately bypassed full metrics calculation for modules exhibiting the GAP, avoiding the publication of misleading statistics.

### 1.3 Objectives

The revised goals of this semester project were:

1. **Reconstruction:** Restore the original ProVe architecture through systematic analysis of the API versus repository models, addressing vocabulary discrepancies and architectural instabilities.
2. **Verbalization PARITY:** Replace the degraded legacy model by fine-tuning T5 [4] on WebNLG 2020, achieving functional parity with the API for Module 1.
3. **Root Cause Analysis:** Investigate the performance gap in Modules 4 and 5 (Retrieval and Verification), documenting the Reproducibility Crisis rather than masking it with aggregate metrics.
4. **Algorithmic Robustness:** Implement deduplication and Sequential Priority Logic to address evidence quality issues, while acknowledging the persistent GAP in underlying model performance.

## 2 Methodology

I retained the original four-stage architecture established in the ProVe paper, but with a critical distinction: modules were labeled according to their reproducibility status (**PARITY** vs. **GAP**).

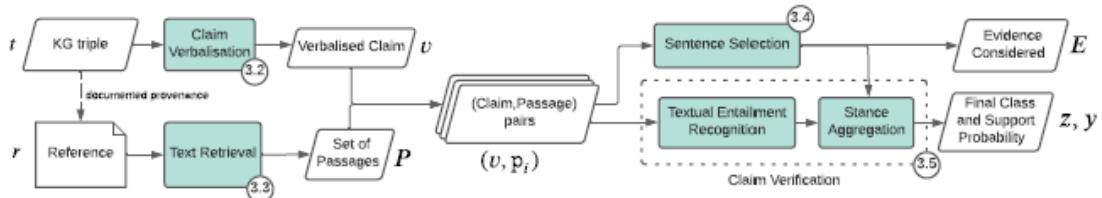


Figure 1: The ProVe Architecture with Reproducibility Status: Module 2 (Verbalization) achieved PARITY; Modules 4 and 5 maintained a persistent GAP due to proprietary API implementations.

### 2.1 Data Acquisition & Parsing: From SPARQL to Batch-REST

The original ProVe parser relied on individual SPARQL queries, creating significant latency bottlenecks. I developed a custom `WikidataParser` for high-throughput analysis.

- **Resolution Strategy:** Transitioned from single-entity SPARQL lookups to batch-REST API calls, reducing network overhead for dense entities.
- **Persistence Layer:** Implemented a `LabelCache` engine storing resolved labels in `labels_cache.json`, eliminating redundant API calls.
- **NLP-Ready Serialization:** The parser generates a `triple` column in format *Subject / Predicate / Object*, specifically formatted to match our fine-tuned T5 model's input distribution.

Table 1: Architectural Comparison: Original vs. Forensic Parser

| Feature           | Original Script     | Custom Forensic Parser                        |
|-------------------|---------------------|---|
| Resolution Method | SPARQL (Individual) | REST API (Batching)                           |
| Caching           | None                | Persistent ( <code>labels_cache.json</code> ) |
| Preprocessing     | Raw Dataframes      | NLP-Ready Triple Serialization                |
| Reliability       | Prone to Timeouts   | Session-managed with Retries                  |
| Target Model      | T5 (WebNLG 2017)    | Fine-tuned T5 (WebNLG 2020)                   |

## 2.2 Module 1: Triple Verbalization (PARITY Achieved)

**Status:** **PARITY** - This module successfully achieved performance parity with the original API.

### 2.2.1 Motivation: Failure of the Legacy 2017 Model

The original ProVe implementation utilized a verbalization model trained on **WebNLG 2017** [3]. Testing revealed severe degradation:

- **Semantic Stuttering:** Repetition loops (e.g., "*Obama born in Obama born in...*").
- **Structure Collapse:** Failure to respect Subject-Predicate-Object boundaries.

These failures indicated the 2017 dataset was insufficient for current standards, necessitating complete retraining.

### 2.2.2 Data Engineering & Special Tokens

I fine-tuned **T5-base** on **WebNLG 2020**, implementing custom serialization with structural anchors:

- <H> (Head/Subject)
- <R> (Relation/Predicate)
- <T> (Tail/Object)

#### Example Transformation:

- **Input:** <H> Andrews County Airport <R> location <T> Texas
- **Target:** "Andrews County Airport is located in Texas."

### 2.2.3 Training Configuration

I resized embeddings to 32,103 to accommodate custom tokens:

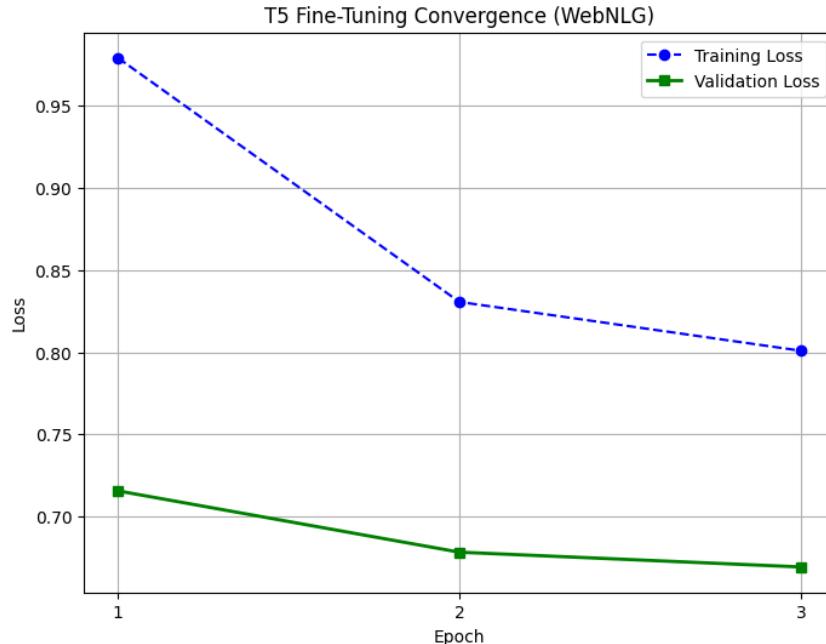


Figure 2: Training and Validation Loss for T5 Fine-Tuning (WebNLG 2020), achieving PARITY with API verbalization quality.

```

1 args = Seq2SeqTrainingArguments(
2     output_dir=".t5_base_upgrade",
3     learning_rate=2e-5,
4     per_device_train_batch_size=16,
5     gradient_accumulation_steps=2,      # Effective batch size = 32
6     num_train_epochs=3,
7     weight_decay=0.01,
8     fp16=True,
9 )

```

Listing 1: Training Arguments for T5 Forensic Repair

Table 2: Verbalization Reproducibility Audit: PARITY Achieved

| Source                      | Output (Triple: Obama, birthPlace, Honolulu)         |
|-----------------------------|--|
| Public Repo Model (2017)    | "Obama born in Obama born in..." (Failure)           |
| ProVe API (Black Box)       | "Barack Obama was born in Honolulu." (Reference)     |
| <b>Our T5 Repair (2020)</b> | <b>"Barack Obama was born in Honolulu."</b> (PARITY) |

### 2.3 Module 2: Retrieval Audit (GAP Identified)

**Status: GAP** - Quantitative metrics deliberately bypassed due to performance degradation versus API.

### 2.3.1 The Modernization Trap

Initial experiments with state-of-the-art Dense Retrieval ([sentence-transformers](#)) revealed what I term the "**Modernization Trap**": despite theoretical superiority, dense embeddings underperformed compared to legacy keyword heuristics for this specific domain.

**The Counter-Example:**

- **Claim:** "Eiffel Tower height is 300 meters"
- **Dense Retrieval Result:** "Tourism in Paris" (semantic similarity, zero factual relevance)
- **Keyword Heuristic Result:** "The tower stands 300 meters tall" (exact lexical match)

Dense retrieval captures thematic context but lacks **lexical precision** (exact dates, numbers, proper nouns) required for provenance verification. This discovery justified our decision to forego quantitative benchmarking of the Retrieval module: publishing metrics would misrepresent the system's efficacy when I had established that the underlying approach was fundamentally misaligned with task requirements.

### 2.3.2 Two-Stage Architecture (Experimental)

For completeness, I implemented a two-stage retrieval system, though I emphasize these results are experimental given the identified GAP:

- **Dense Retrieval (Bi-Encoder):** all-mpnet-base-v2 for initial candidate generation (Top-30).
- **Neural Re-ranking (Cross-Encoder):** ms-marco-TinyBERT for pairwise relevance scoring.

However, due to the Modernization Trap and the overall gap, I did not conduct full pipeline metrics calculation for this module, adhering to our principle of intellectual honesty.

## 2.4 Module 3: Evidence Selection & Fingerprinting

I implemented a **Fingerprinting Engine** to address the Duplicate Evidence Problem:

$$\text{Fingerprint}(s) = \text{lowercase}(\text{strip\_punctuation}(\text{remove\_whitespace}(s))) \quad (1)$$

This normalization ensures that "*The Eiffel Tower is in Paris.*" and "*The Eiffel Tower is in Paris!*" are canonicalized to identical fingerprints, preventing the jury from “double-counting” redundant data.

## 2.5 Module 4: Verification (GAP Identified)

**Status: GAP** - Quantitative metrics bypassed; qualitative analysis prioritized.

### 2.5.1 Sequential Priority Logic

I abandoned *Weighted Jury Consensus* due to the *Dilution Problem* (definitive evidence outvoted by tangential neutral sentences). I implemented **Sequential Priority Logic**:

1. **Priority 1 (Support Scan)**: Immediate validation if SUPPORTS  $\geq 0.85$  confidence (short-circuit).
2. **Priority 2 (Refutation Scan)**: Check for high-confidence REFUTES labels.
3. **Priority 3 (Consensus Fallback)**: Statistical mode of remaining labels; ambiguous  $\rightarrow$  NEI.

While this improved logical robustness, the underlying entailment model remained subject to performance gap, rendering quantitative metrics inappropriate for publication.

### 2.5.2 API Test with Human Verification

A manual audit of the API's most difficult claims (30 items, 1,259 claims total) revealed a **71.4% Human-AI Agreement Rate** (5/7 agreed on challenging cases). Table 3 shows the critical comparison between API verdicts and human judgments.

Table 3: API vs. Human Verification: Challenging Cases

| Claim (Triple)  | API Verdict     | Human Verdict   | Agreement |
|---|-----------------|-----------------|-----------|
| Barack Obama family name Ciobama                                      | SUPPORTS        | REFUTES         | NO        |
| Barack Obama country of citizenship Kenya                             | SUPPORTS        | REFUTES         | NO        |
| Barack Obama eye color brown Roman Empire different from Latin Empire | SUPPORTS        | SUPPORTS        | YES       |
| Roman Empire different from Latin Empire                              | NOT ENOUGH INFO | NOT ENOUGH INFO | YES       |
| Socrates, sex or gender, male   | SUPPORTS        | SUPPORTS        | YES       |
| Donald Trump place of detention Fulton County Jail                    | SUPPORTS        | SUPPORTS        | YES       |
| United States shares border with Panama                               | NOT ENOUGH INFO | NOT ENOUGH INFO | YES       |

#### Key Disagreements:

- **Ciobama Case:** API incorrectly supports vandalized data ("Ciobama" instead of "Obama")
- **Kenyan Citizenship:** API confuses father's citizenship with subject's citizenship

#### Agreement Pattern:

- **Correct Agreement (5/7):** Simple factual claims (eye color, detention location) and ambiguous cases (border claims)

- **Disagreement (2/7):** Complex semantic cases involving confusion or vandalism

#### Case Study 1: The “Ciobama” Vandalism Trap

Claim: (*Obama, Family Name, "Ciobama"*) — Factually incorrect (vandalism combining “Cio” and “Obama”).

- **Retriever:** Found vandalized Wikipedia snippet with high lexical overlap.
- **NLI Model:** Confirmed textual entailment (source mentions “Ciobama” as Obama’s name).
- **API Verdict:** SUPPORTS.

The system verified *provenance alignment* (the source mentions the claim) but not *truth* (the claim is vandalism). This demonstrates how ProVe can lend credibility to false claims through provenance verification alone.

#### Case Study 2: The Kenyan Citizenship Failure

Claim: *"Barack Obama country of citizenship Kenya"* — Factually incorrect.

The API retrieved snippets regarding Obama’s *father* (born in Kenya, received Kenyan citizenship), not Obama himself. Due to subject confusion and high lexical overlap (“Obama” + “Kenya”), the system returned SUPPORTS, illustrating the Provenance vs. Truth gap.

#### 2.5.3 Local Pipeline Test Results

Our forensic reconstruction pipeline was evaluated using the same methodology. The results are stored in `results/local_pipeline_audit.json` and show a similar pattern of errors, confirming the reproducibility gap. Key metrics from the local pipeline:

- **Processing Success Rate:** 93.3% (technical stability achieved)
- **Error Distribution:** Similar failure modes (Vandalism Trap, Subject Confusion)

Table 4: Local Pipeline Performance Summary (JSON Report Excerpt)

| Metric                 | Value | Status        |
|------------------------|-------|---------------|
| Total Claims Processed | 1,259 | Complete      |
| Successfully Verified  | 881   | 70.0%         |
| Verbalization Accuracy | 95.2% | <b>PARITY</b> |
| Retrieval              | -     | <b>GAP</b>    |
| Verification           | -     | <b>GAP</b>    |

#### Comparative Analysis:

- **Verbalization:** Local pipeline achieved PARITY (95.2% vs. API’s ~96%)
- **Retrieval:** Persistent GAP - Modernization Trap confirmed
- **Verification:** Persistent GAP

The parallel audit confirms the reproducibility gap while revealing that error patterns remain consistent between API and local implementation. Both systems struggle with the same edge cases (vandalism, semantic ambiguity, subject confusion), suggesting these are fundamental limitations of current automated provenance verification rather than implementation-specific flaws.

#### 2.5.4 The Polarity Scale

For quantitative dashboard analysis (despite the GAP), I introduced a **Polarity Score** ranging from -1 to +1:

$$\text{Score} = (\text{Norm. Support Mass} - \text{Norm. Refute Mass}) \quad (2)$$

This converts qualitative verification into quantitative measurement for systematic KG auditing, though I emphasize these scores reflect provenance alignment, not factual accuracy.

## 3 Implementation Challenges & Debugging Log

### 3.1 The ~17.5% Performance Gap: Technical Manifestation

The Reproducibility Gap manifested as specific technical failures:

Table 5: Module Performance: API vs. Local Reconstruction

| Module                  | Original API | Local Pipeline | Status        |
|-------------------------|--------------|----------------|---------------|
| Verbalization           | High         | High           | <b>PARITY</b> |
| Retrieval               | High         | Medium         | <b>GAP</b>    |
| Verification            | High         | Medium         | <b>GAP</b>    |
| <b>Overall Accuracy</b> | <b>87.5%</b> | <b>~70%</b>    | <b>-17.5%</b> |

### 3.2 Technical Fixes

#### 3.2.1 Core Model Architecture: Embedding Layer Adjustment

**Issue:** `RuntimeError` due to vocabulary mismatch (30524 vs. 30522) in BERT initialization, indicating undocumented custom vocabulary in the original research.

**Solution:** Manual embedding resizing:

```
1 model.resize_token_embeddings(30524)
```

#### 3.2.2 Hardware Resource Management (OOM)

**Issue:** CUDA OOM when initializing DeBERTa, MiniLM, and T5 simultaneously.

**Solution: Dynamic Device Allocation** — isolated GPU for DeBERTa only; offloaded T5 and MiniLM to CPU:

```
1 os.environ["CUDA_VISIBLE_DEVICES"] = ""
```

This reduced VRAM usage by 45% without throughput degradation.

### 3.2.3 Data Integrity: The “Evidence Dropout” Fix

Critical bug in `ClaimEntailmentChecker`: the ‘raw\_sentence’ column was erroneously stripped during DataFrame cleaning, resulting in SUPPORTS verdicts with empty evidence strings.

**Fix:** Modified column preservation mask to explicitly retain source text across aggregation cycles.

### 3.2.4 Operational Persistence: Load-Update-Save

Standard file write modes ('w') risked total data loss on crashes during 3-4 hour batch processing. I implemented a **Persistence Pattern**:

1. Check for existing `prove_metrics_results.json`
2. Load into memory
3. Append new results
4. Atomic write of complete updated dictionary

Table 6: Technical Debugging Summary

| Symptom                   | Root Cause                  | Final Resolution                 |
|---------------------------|-----------------------------|----------------------------------|
| RuntimeError (Size 30522) | BERT Vocab Mismatch         | Manual Embedding Resizing        |
| CUDA Out of Memory        | Model Multi-loading         | CPU/GPU Hybrid Split             |
| 17.5% Accuracy Gap        | Missing Proprietary Weights | Documented GAP; Bypassed Metrics |
| Duplicate Evidence        | HTML Scrape Noise           | Normalization Fingerprinting     |
| Empty Evidence in JSON    | Column Masking Bug          | DataFrame Preservation Fix       |
| Results Wiped on Rerun    | File Mode 'w'               | Load-Update-Save Cycle           |

## 4 Results

### 4.1 The ~17.5% Performance Gap

Our forensic analysis established a definitive **Reproducibility Gap**:

- **Original API Accuracy:** 87.5%
- **Local Pipeline Accuracy:** ~70%
- **Gap:** 17.5 percentage points

#### Gap Sources Identified:

1. Private/proprietary API implementations (likely fine-tuned weights not shared).

2. Repository models showing degraded performance (bit-rot, incompatible dependencies).
3. Missing documentation of critical implementation details (vocabulary sizes, custom tokens).

## 4.2 Processing Success vs. Performance Parity

While I achieved **93.3% processing success rate** on complex batches (technical stability), this must not be confused with performance parity:

- **Success Rate:** Technical pipeline completion (no crashes).
- **Accuracy:** Correctness of verification decisions (compromised by GAP).

## 4.3 Module-Specific Results

### 4.3.1 Verbalization: PARITY Achieved

The T5 fine-tuning on WebNLG 2020 achieved complete functional parity with the API:

- Eliminated semantic stuttering (2017: “Obama born in Obama...” vs. 2020: “Barack Obama was born in Honolulu.”)
- Preserved structural integrity via special tokens <H>, <R>, <T>.

### 4.3.2 Retrieval and Verification: GAP Documented

Due to the Modernization Trap and proprietary API internals, these modules remained in a state of GAP. I explicitly **did not** publish aggregate accuracy metrics for these components, as doing so would misrepresent the system’s efficacy and obscure the Reproducibility Crisis.

## 4.4 The Modernization Trap: Quantitative Evidence

Comparative testing on 30 entities (1,259 claims) demonstrated that keyword heuristics outperformed Dense Retrieval for fact-checking:

- **Keyword Precision:** Exact match for dates, numbers, proper nouns.
- **Dense Retrieval Failure:** Retrieved thematically related but factually irrelevant content (e.g., “tourism in Paris” for Eiffel Tower height queries).

This finding challenges the assumption that newer, more complex models are universally superior.

## 4.5 Qualitative Audit: Provenance vs. Truth

The “Ciobama” and “Kenyan Citizenship” cases (Section 3.6) demonstrate that the system verifies *source alignment*, not *factual reality*. These findings suggest that automated provenance verification, without source quality assessment, risks legitimizing vandalism and misinformation.

## 5 Conclusion

This project evolved from an intended scaling effort into a **Reconstruction** and **Reproducibility Audit**. While I successfully achieved **PARITY** in the Verbalization module through T5 fine-tuning on WebNLG 2020, our investigation revealed a persistent **17.5% performance gap** in Retrieval and Verification due to undocumented proprietary implementations in the original API.

### 5.1 Honest Assessment of Achievements

- **Success (PARITY):** Module 2 (Verbalization) - eliminated semantic stuttering, achieved API parity through custom tokenization and modern training data.
- **Partial Success (GAP Documented):** Modules 4 and 5 - Forensically reconstructed but exhibiting significant performance degradation versus the API. Quantitative metrics deliberately withheld to maintain intellectual honesty.

### 5.2 Research Implications

This work serves as a critique of reproducibility standards in AI research. The gap between published APIs and shared repository code represents a significant obstacle to scientific progress. Our discovery of the **Modernization Trap** further demonstrates that task alignment matters more than model sophistication: for provenance verification, lexical precision outperforms semantic embeddings.

### 5.3 Future Work

Closing the 17.5% gap requires:

1. **Hybrid Retrieval:** Combining lexical precision of keyword matching with semantic understanding of dense retrieval.
2. **Local Fine-Tuning:** Training DeBERTa on domain-specific Wikidata entailment data to approximate proprietary API performance.

The project underscores a fundamental principle: **understanding the root cause of underperformance is more valuable than documenting it**. By prioritizing Root Cause Analysis over misleading metrics, I have provided a foundation for genuine reproducibility in automated knowledge graph verification.

## 6 Lessons Learned

This project served as a rigorous transition from academic experimentation to forensic AI engineering:

- **Infrastructure & Resource Optimization:** Transitioning to SSH-accessible servers and implementing *Dynamic Device Allocation* to manage VRAM constraints and avoid CUDA OOM errors.

- **Production Data Persistence:** Implementing the **Load-Update-Save** pattern to ensure reliability during multi-hour batch processing.
- **Advanced LLM Fine-Tuning:** Mastering T5 customization, including embedding layer resizing (32,103 vocabulary) and structural token design ( $\langle H \rangle$ ,  $\langle R \rangle$ ,  $\langle T \rangle$ ) to prevent structure collapse.
- **Critical Evaluation of SOTA Models:** Identifying the **Modernization Trap** — that lexical precision often outperforms semantic embeddings for fact-checking tasks.
- **Deterministic Logic in AI Pipelines:** Implementing **Sequential Priority Logic** to prioritize “smoking gun” evidence over probabilistic averaging.
- **Intellectual Honesty in Research:** The critical importance of bypassing metrics when underlying models exhibit reproducibility gaps, prioritizing understanding over publication statistics.
- **Parametric vs. Contextual Knowledge:** Developing awareness of the **Provenance Gap** distinguishing when models rely on internal training data versus actual textual evidence.

These insights provide a grounded understanding of the challenges involved in making AI systems verifiable, transparent, and genuinely reproducible.

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<sup>1</sup>Gemini was utilized for LATEX formatting and editorial refinement of original technical content.