# TASK 2: RAG (RETRIVER ARGUMENTED GENERATION)

In [ ]:

```
# Install required packages
%pip install numpy pandas seaborn matplotlib tqdm sentence-transformers faiss-
```

In [1]:

```
import os
import math
import json
import numpy as np
import faiss
from typing import List, Dict, Any, Tuple
from dataclasses import dataclass, field
from collections import defaultdict
import matplotlib.pyplot as plt
import seaborn as sns
import pandas as pd
from tqdm import tqdm
import warnings
warnings.filterwarnings('ignore')

import dspy
from sentence_transformers import SentenceTransformer
import PyPDF2
sns.set_style("whitegrid")
plt.rcParams['figure.figsize'] = (14, 8)

print("All imports successful")
```

```
All imports successful
```

LLM INITILIZATION (If Using Grok)

In [ ]:

```
%pip install getpass langchain_groq langchain_core
```

In [2]:

```
import getpass
api_key = getpass.getpass("Enter your GROQ API key: ")

from langchain_groq import ChatGroq
from langchain_core.messages import HumanMessage, SystemMessage

class GroqLM(dspy.LM):
    def __init__(self, model="llama-3.3-70b-versatile", api_key=None, **kwargs
        super().__init__(model=model, **kwargs)
        self.model_name = model
        self.client = ChatGroq(model=model, api_key=api_key)

    def __call__(self, prompt=None, messages=None, **kwargs):
        if messages:
            lc_messages = []
            for msg in messages:
                if msg.get("role") == "system":
                    lc_messages.append(SystemMessage(content=msg["content"]))
                elif msg.get("role") == "user":
                    lc_messages.append(HumanMessage(content=msg["content"]))
            response = self.client.invoke(lc_messages)
        else:
            response = self.client.invoke([HumanMessage(content=prompt)])
        return [response.content]

# Initialize LM (use your actual API key)
lm = GroqLM(api_key=api_key)
dspy.configure(lm=lm)
```

PDF EXTRACTION AND TEXT PROCESSING

In [4]:

```
def extract_pdf_text(path: str) -> str:
    """Extract text from PDF file"""
    text = ""
    with open(path, "rb") as f:
        reader = PyPDF2.PdfReader(f)
        for page in reader.pages:
            page_text = page.extract_text() or ""
            text += page_text + "\n"
    return text

def normalize_text(s: str) -> str:
    """Normalize text for comparison"""
    import re
    s = s.lower().strip()
    s = re.sub(r"[^a-z0-9\s]", " ", s)
    s = " ".join(s.split())
    return s

def chunk_text(text: str, max_chars: int = 800, overlap: int = 100) -> List[st
    """Chunk text with overlap"""
    chunks = []
    start = 0
    while start < len(text):
        end = min(len(text), start + max_chars)
        chunk = text[start:end]
        chunks.append(chunk.strip())
        if end == len(text):
            break
        start = end - overlap
    return [c for c in chunks if c]
```

EMBEDDING AND VECTOR INDEX

In [5]:

```
# Initialize embedding model globally
embed_model = SentenceTransformer("all-MiniLM-L6-v2")
```

```python
def embed_texts(texts: List[str]) -> np.ndarray:
    """Generate embeddings for texts"""
    return np.array(embed_model.encode(texts, convert_to_numpy=True), dtype="f

class VectorIndex:
    """FAISS-based vector index for retrieval"""

    def __init__(self, chunks: List[str]):
        self.chunks = chunks
        embeddings = embed_texts(chunks)
        dim = embeddings.shape[1]
        self.index = faiss.IndexFlatIP(dim)
        # Normalize for cosine similarity
        faiss.normalize_L2(embeddings)
        self.embeddings = embeddings
        self.index.add(self.embeddings)

    def search(self, query: str, k: int = 4) -> List[Dict[str, Any]]:
        """Search for top-k similar chunks"""
        q_emb = embed_texts([query])
        faiss.normalize_L2(q_emb)
        scores, idxs = self.index.search(q_emb, k)
        idxs = idxs[0]
        scores = scores[0]
        results = []
        for i, s in zip(idxs, scores):
            if i == -1:
                continue
            results.append({"text": self.chunks[i], "score": float(s), "idx":
        return results
```

LOAD AND INDEX PDF

In [11]:

```python
# Load PDF
pdf_path = "/mnt/a/Projects/Prompt_Optimizer/pdfs/Why Machines Learn PDF.pdf"
print(f"\nLoading PDF: {pdf_path}")

doc_text = extract_pdf_text(pdf_path)
doc_text = normalize_text(doc_text)
chunks = chunk_text(doc_text, max_chars=800, overlap=100)
vector_index = VectorIndex(chunks)

print(f" Built index with {len(chunks)} chunks")
print(f"  Document length: {len(doc_text):,} characters")
```

```
Loading PDF: /mnt/a/Projects/Prompt_Optimizer/pdfs/Why Machines Learn PDF.pdf
 Built index with 161 chunks
  Document length: 112,762 characters
```

BASELINE RAG SYSTEM

In [12]:

```python
class RAGQASignature(dspy.Signature):
    """Answer a question using retrieved context from a PDF."""
    question: str = dspy.InputField(desc="User question about the PDF.")
    contexts: List[str] = dspy.InputField(desc="List of retrieved passages fro

    answer: str = dspy.OutputField(desc="Final answer grounded in the providec
    answer_confidence: float = dspy.OutputField(desc="Self-estimated confidenc
    faithfulness_score: float = dspy.OutputField(
        desc="Self-rated how well the answer is supported by the contexts, 0–1
    )
    coverage_score: float = dspy.OutputField(
        desc="Self-rated how completely the answer covers relevant info, 0–1."
    )

class BaselineRAG(dspy.Module):
    """Baseline RAG QA System"""

    def __init__(self, index: VectorIndex, k: int = 4):
        super().__init__()
        self.index = index
        self.k = k
        self.qa = dspy.ChainOfThought(RAGQASignature)

    def retrieve(self, question: str) -> List[str]:
        """Retrieve relevant chunks"""
        results = self.index.search(question, k=self.k)
        return [r["text"] for r in results]

    def forward(self, question: str):
        """Execute RAG pipeline"""
        contexts = self.retrieve(question)
        joined_contexts = [f"[Chunk {i+1}]\n{c}" for i, c in enumerate(context

        result = self.qa(question=question, contexts=joined_contexts)

        return dspy.Prediction(
            question=question,
            contexts=joined_contexts,
            answer=result.answer,
            answer_confidence=result.answer_confidence,
            faithfulness_score=result.faithfulness_score,
            coverage_score=result.coverage_score,
        )
```

GEPA COMPONENTS - PROMPT CANDIDATE STRUCTURE

In [28]:

```
@dataclass
class RAGPromptCandidate:
    """Prompt candidate for RAG optimization"""

    # Retrieval instructions
    retrieval_instruction: str
    reranking_strategy: str
    # Generation instructions
    generation_prefix: str
    answer_format: str
    grounding_emphasis: str

    # Metadata
    score: float = 0.0
    performance_metrics: Dict[str, float] = field(default_factory=dict)

    def to_dict(self):
        return {
            'retrieval_instruction': self.retrieval_instruction,
            'reranking_strategy': self.reranking_strategy,
            'generation_prefix': self.generation_prefix,
            'answer_format': self.answer_format,
            'grounding_emphasis': self.grounding_emphasis,
            'score': self.score,
            'performance_metrics': self.performance_metrics
        }
```

GEPA - CANDIDATE POOL INITIALIZATION

In [13]:

```
class RAGCandidatePoolInitializer:
    """Initialize diverse pool of RAG prompt candidates"""

    def __init__(self, pool_size: int = 12):
        self.pool_size = pool_size

    def generate_initial_pool(self) -> List[RAGPromptCandidate]:
        """Generate diverse RAG prompt candidates"""

        # Retrieval instructions
        retrieval_instructions = [
            "Find the most relevant passages that directly answer the questior
            "Locate comprehensive context covering all aspects of the query",
            "Identify precise excerpts that contain factual answers",
            "Retrieve diverse perspectives related to the question",
        ]

        # Reranking strategies
        reranking_strategies = [
            "prioritize semantic relevance",
            "balance relevance with diversity",
            "focus on factual density",
            "optimize for answer completeness",
        ]

        # Generation prefixes
        generation_prefixes = [
            "Based strictly on the provided context",
            "Synthesizing information from the retrieved passages",
            "Drawing directly from the source material",
            "Grounding the response in the given context",
        ]

        # Answer formats
        answer_formats = [
            "provide a clear, concise answer",
            "construct a detailed explanation",
            "deliver a structured response",
            "formulate a comprehensive answer",
        ]

        # Grounding emphasis
        grounding_emphases = [
            "Ensure every claim is supported by the context",
            "Maintain high fidelity to source information",
            "Quote or paraphrase directly when appropriate",
            "Stay faithful to the retrieved facts",
        ]

        candidates = []
        np.random.seed(42)

        for i in range(self.pool_size):
            candidate = RAGPromptCandidate(
                retrieval_instruction=np.random.choice(retrieval_instructions)
                reranking_strategy=np.random.choice(reranking_strategies),
                generation_prefix=np.random.choice(generation_prefixes),
                answer_format=np.random.choice(answer_formats),
                grounding_emphasis=np.random.choice(grounding_emphases)
            )
            candidates.append(candidate)

        return candidates

    def visualize_pool_diversity(self, candidates: List[RAGPromptCandidate]):
        """Visualize candidate pool diversity"""

        # Create feature matrix
        features = []
        for c in candidates:
            feature = f"{c.retrieval_instruction} {c.reranking_strategy} {c.ge
            features.append(feature)

        # Compute embeddings
        embeddings = embed_texts(features)

        # Compute similarity matrix
        from sklearn.metrics.pairwise import cosine_similarity
        similarities = cosine_similarity(embeddings)

        # Plot
        plt.figure(figsize=(12, 10))
        sns.heatmap(similarities, annot=True, fmt='.2f', cmap='viridis',
                    xticklabels=[f"C{i+1}" for i in range(len(candidates))],
                    yticklabels=[f"C{i+1}" for i in range(len(candidates))],
                    cbar_kws={'label': 'Cosine Similarity'})
        plt.title("RAG Candidate Pool Diversity Matrix", fontsize=16, fontweig
        plt.xlabel("Candidate ID", fontsize=12)
        plt.ylabel("Candidate ID", fontsize=12)
        plt.tight_layout()
        plt.savefig('rag_candidate_diversity.png', dpi=300, bbox_inches='tight
        plt.show()

        avg_sim = similarities[np.triu_indices_from(similarities, k=1)].mean()
        print(f"\n✓ Generated {len(candidates)} diverse RAG candidates")
        print(f"  Average pairwise similarity: {avg_sim:.3f}")
        print(f"  Diversity score: {1 - avg_sim:.3f}")
```

GEPA - PARETO-BASED FILTERING

In [14]:

```
class RAGParetoFilter:
    """Multi-objective Pareto filtering for RAG"""

    def __init__(self, objectives: List[str]):
        self.objectives = objectives

    def dominates(self, cand_a: RAGPromptCandidate, cand_b: RAGPromptCandidate
        """Check if A Pareto-dominates B"""
        metrics_a = cand_a.performance_metrics
        metrics_b = cand_b.performance_metrics

        better_in_any = False
        worse_in_any = False

        for obj in self.objectives:
            val_a = metrics_a.get(obj, 0)
            val_b = metrics_b.get(obj, 0)

            if val_a > val_b:
                better_in_any = True
            elif val_a < val_b:
                worse_in_any = True

        return better_in_any and not worse_in_any

    def get_pareto_front(self, candidates: List[RAGPromptCandidate]) -> List[R
        """Extract Pareto-optimal candidates"""
        pareto_front = []

        for cand in candidates:
            is_dominated = False
            for other in candidates:
                if cand != other and self.dominates(other, cand):
                    is_dominated = True
                    break

            if not is_dominated:
                pareto_front.append(cand)

        return pareto_front

    def visualize_pareto_front(self, candidates: List[RAGPromptCandidate],
                               pareto_front: List[RAGPromptCandidate],
                               iteration: int = 0):
        """Visualize Pareto front in 2D and 3D"""

        if len(self.objectives) < 2:
            print("Need at least 2 objectives")
            return

        obj1, obj2 = self.objectives[0], self.objectives[1]

        # Extract metrics
        all_x = [c.performance_metrics.get(obj1, 0) for c in candidates]
        all_y = [c.performance_metrics.get(obj2, 0) for c in candidates]

        pareto_x = [c.performance_metrics.get(obj1, 0) for c in pareto_front]
        pareto_y = [c.performance_metrics.get(obj2, 0) for c in pareto_front]

        # Create figure
        fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(16, 6))

        # 2D Plot
        ax1.scatter(all_x, all_y, c='lightblue', s=150, alpha=0.6,
                   label='All Candidates', edgecolors='navy', linewidths=1.5)
        ax1.scatter(pareto_x, pareto_y, c='red', s=250, alpha=0.9,
                   label='Pareto Front', marker='*', edgecolors='darkred', lir

        ax1.set_xlabel(obj1.replace('_', ' ').title(), fontsize=13, fontweight
        ax1.set_ylabel(obj2.replace('_', ' ').title(), fontsize=13, fontweight
        ax1.set_title(f'Pareto Front (Iteration {iteration})', fontsize=14, fc
        ax1.legend(fontsize=11, loc='best')
        ax1.grid(True, alpha=0.3)

        # 3D Plot if we have 3 objectives
        if len(self.objectives) >= 3:
            obj3 = self.objectives[2]
            all_z = [c.performance_metrics.get(obj3, 0) for c in candidates]
            pareto_z = [c.performance_metrics.get(obj3, 0) for c in pareto_frc

            from mpl_toolkits.mplot3d import Axes3D
            ax2 = fig.add_subplot(122, projection='3d')

            ax2.scatter(all_x, all_y, all_z, c='lightblue', s=100, alpha=0.6,
                       label='All Candidates', edgecolors='navy')
            ax2.scatter(pareto_x, pareto_y, pareto_z, c='red', s=200, alpha=0.
                       label='Pareto Front', marker='*', edgecolors='darkred',

            ax2.set_xlabel(obj1.replace('_', ' ').title(), fontsize=11)
            ax2.set_ylabel(obj2.replace('_', ' ').title(), fontsize=11)
            ax2.set_zlabel(obj3.replace('_', ' ').title(), fontsize=11)
            ax2.set_title('3D Pareto Front', fontsize=14, fontweight='bold')
            ax2.legend(fontsize=10)
        else:
            # Show candidate count distribution
            score_ranges = [0.0, 0.3, 0.5, 0.7, 0.9, 1.0]
            all_scores = [c.score for c in candidates]
            pareto_scores = [c.score for c in pareto_front]

            ax2.hist([all_scores, pareto_scores], bins=20, label=['All', 'Pare
                    color=['lightblue', 'red'], alpha=0.7, edgecolor='black')
            ax2.set_xlabel('Overall Score', fontsize=12, fontweight='bold')
            ax2.set_ylabel('Count', fontsize=12, fontweight='bold')
            ax2.set_title('Score Distribution', fontsize=14, fontweight='bold'
            ax2.legend(fontsize=11)
            ax2.grid(True, alpha=0.3, axis='y')

        plt.tight_layout()
        plt.savefig(f'rag_pareto_front_iter{iteration}.png', dpi=300, bbox_inc
        plt.show()

        print(f"\n✓ Pareto front: {len(pareto_front)}/{len(candidates)} candic

print("✓ Pareto filter ready")

# ============================================================================
# BLOCK 9: GEPA - REFLECTIVE PROMPT MUTATION
# ============================================================================

class RAGReflectiveMutator:
    """Reflective mutation for RAG prompts"""

    def __init__(self):
        self.mutation_history = []

    def analyze_performance(self, candidate: RAGPromptCandidate) -> Dict[str,
        """Analyze candidate performance"""
        metrics = candidate.performance_metrics

        analysis = {
            'strengths': [],
            'weaknesses': [],
            'suggestions': []
        }

        # Analyze retrieval
        ret_recall = metrics.get('retrieval_recall', 0)
        if ret_recall > 0.8:
            analysis['strengths'].append("Excellent retrieval recall")
        elif ret_recall < 0.5:
            analysis['weaknesses'].append("Poor retrieval quality")
            analysis['suggestions'].append("Refine retrieval instruction for b
        # Analyze generation
        gen_f1 = metrics.get('generation_f1', 0)
        if gen_f1 > 0.7:
            analysis['strengths'].append("High-quality answer generation")
        elif gen_f1 < 0.5:
            analysis['weaknesses'].append("Weak answer quality")
            analysis['suggestions'].append("Improve generation grounding and f

        # Analyze faithfulness
        faithfulness = metrics.get('faithfulness', 0)
        if faithfulness < 0.7:
            analysis['weaknesses'].append("Low faithfulness to context")
            analysis['suggestions'].append("Strengthen grounding emphasis")

        return analysis

    def mutate_candidate(self, candidate: RAGPromptCandidate) -> RAGPromptCanc
        """Apply intelligent mutations"""
        analysis = self.analyze_performance(candidate)

        # Copy original
        new_retrieval = candidate.retrieval_instruction
        new_reranking = candidate.reranking_strategy
        new_generation = candidate.generation_prefix
        new_format = candidate.answer_format
        new_grounding = candidate.grounding_emphasis

        # Apply mutations based on weaknesses
        if "Poor retrieval quality" in str(analysis['weaknesses']):
            new_retrieval = "Identify the most semantically relevant and factu
            new_reranking = "prioritize semantic relevance and factual accurac

        if "Weak answer quality" in str(analysis['weaknesses']):
            new_generation = "Carefully synthesizing key information from the
            new_format = "provide a precise, well-structured answer"

        if "Low faithfulness to context" in str(analysis['weaknesses']):
            new_grounding = "Ensure every statement is directly grounded in th

        mutated = RAGPromptCandidate(
            retrieval_instruction=new_retrieval,
            reranking_strategy=new_reranking,
            generation_prefix=new_generation,
            answer_format=new_format,
            grounding_emphasis=new_grounding
        )

        self.mutation_history.append({
            'original': candidate.to_dict(),
            'mutated': mutated.to_dict(),
            'analysis': analysis
        })
        return mutated

    def visualize_mutation_impact(self):
        """Visualize mutation effectiveness"""
        if not self.mutation_history:
            print("No mutations yet")
            return

        mutations = range(len(self.mutation_history))
        improvements = [
            entry['mutated']['score'] - entry['original']['score']
            for entry in self.mutation_history
        ]

        # Bar plot
        plt.figure(figsize=(12, 6))
        colors = ['green' if x > 0 else 'red' if x < 0 else 'gray' for x in im
        bars = plt.bar(mutations, improvements, color=colors, alpha=0.7, edgec

        plt.axhline(y=0, color='black', linestyle='--', linewidth=2)
        plt.xlabel('Mutation ID', fontsize=13, fontweight='bold')
        plt.ylabel('Score Improvement', fontsize=13, fontweight='bold')
        plt.title('Reflective Mutation Impact Analysis', fontsize=15, fontweig
        plt.grid(True, alpha=0.3, axis='y')

        # Add value labels on bars
        for bar, val in zip(bars, improvements):
            height = bar.get_height()
            plt.text(bar.get_x() + bar.get_width()/2., height,
                    f'{val:.3f}', ha='center', va='bottom' if val > 0 else 'to
                    fontsize=9, fontweight='bold')

        plt.tight_layout()
        plt.savefig('rag_mutation_impact.png', dpi=300, bbox_inches='tight')
        plt.show()

        avg_improvement = np.mean(improvements)
        positive_mutations = sum(1 for x in improvements if x > 0)
        print(f"\n✓ Mutations analyzed: {len(improvements)}")
        print(f"  Average improvement: {avg_improvement:.3f}")
        print(f"  Positive mutations: {positive_mutations}/{len(improvements)}
```

```
✓ Pareto filter ready
```

In [15]:

```
class RAGSystemAwareMerger:
    """Merge best RAG candidates"""

    def __init__(self):
        self.merge_history = []

    def merge_candidates(self, candidates: List[RAGPromptCandidate],
                        top_k: int = 3) -> RAGPromptCandidate:
        """Intelligently merge top candidates"""
        # Sort by score
        sorted_cands = sorted(candidates, key=lambda x: x.score, reverse=True)

        # Weight by scores
        scores = np.array([c.score for c in sorted_cands])
        weights = scores / scores.sum()

        # Select best components (weighted voting)
        retrieval_options = [c.retrieval_instruction for c in sorted_cands]
        reranking_options = [c.reranking_strategy for c in sorted_cands]
        generation_options = [c.generation_prefix for c in sorted_cands]
        format_options = [c.answer_format for c in sorted_cands]
        grounding_options = [c.grounding_emphasis for c in sorted_cands]

        # Use best candidate's components (could be more sophisticated)
        merged = RAGPromptCandidate(
            retrieval_instruction=retrieval_options[0],
            reranking_strategy=reranking_options[0],
            generation_prefix=generation_options[0],
            answer_format=format_options[0],
            grounding_emphasis=grounding_options[0],
            score=sorted_cands[0].score
        )

        self.merge_history.append({
            'sources': [c.to_dict() for c in sorted_cands],
            'merged': merged.to_dict(),
            'weights': weights.tolist()
        })

        return merged

    def visualize_merge_strategy(self):
        """Visualize merging decisions"""
        if not self.merge_history:
            print("No merges yet")
            return

        fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(16, 6))

        # Merge performance comparison
        merge_ids = []
        source_avgs = []
        merged_scores = []

        for i, entry in enumerate(self.merge_history):
            merge_ids.append(f"Merge {i+1}")
            source_avgs.append(np.mean([s['score'] for s in entry['sources']]))
            merged_scores.append(entry['merged']['score'])

        x = np.arange(len(merge_ids))
        width = 0.35
        ax1.bar(x - width/2, source_avgs, width, label='Avg Source Score',
                color='skyblue', edgecolor='black', linewidth=1.5)
        ax1.bar(x + width/2, merged_scores, width, label='Merged Score',
                color='orange', edgecolor='black', linewidth=1.5)

        ax1.set_xlabel('Merge Operation', fontsize=12, fontweight='bold')
        ax1.set_ylabel('Score', fontsize=12, fontweight='bold')
        ax1.set_title('Merge Performance Comparison', fontsize=14, fontweight=
        ax1.set_xticks(x)
        ax1.set_xticklabels(merge_ids)
        ax1.legend(fontsize=11)
        ax1.grid(True, alpha=0.3, axis='y')

        # Weight distribution for last merge
        if self.merge_history:
            last_merge = self.merge_history[-1]
            weights = last_merge['weights']
            sources = [f"Source {i+1}" for i in range(len(weights))]

            ax2.pie(weights, labels=sources, autopct='%1.1f%%', startangle=90,
                   colors=sns.color_palette('pastel'),
                   wedgeprops={'edgecolor': 'black', 'linewidth': 1.5})
            ax2.set_title('Last Merge Weight Distribution', fontsize=14, fontw

        plt.tight_layout()
        plt.savefig('rag_merge_strategy.png', dpi=300, bbox_inches='tight')
        plt.show()

        print(f"\n✓ Merge operations: {len(self.merge_history)}")
```

GEPA RAG SYSTEM

In [16]:

```
class GEPARAG(dspy.Module):
    """GEPA-optimized RAG system"""

    def __init__(self, index: VectorIndex, k: int = 4, n_iterations: int = 3):
        super().__init__()
        self.index = index
        self.k = k
        self.n_iterations = n_iterations

        # GEPA components
        self.pool_initializer = RAGCandidatePoolInitializer(pool_size=12)
        self.pareto_filter = RAGParetoFilter(
            objectives=['retrieval_recall', 'generation_f1', 'faithfulness']
        )
        self.mutator = RAGReflectiveMutator()
        self.merger = RAGSystemAwareMerger()

        # Optimized components
        self.optimized_candidate = None
        self.optimization_history = []
        # Base QA module
        self.qa = dspy.ChainOfThought(RAGQASignature)

    def optimize(self, eval_questions: List[Dict[str, str]]):
        """Run GEPA optimization"""

        print("\n" + "="*80)
        print("GEPA RAG OPTIMIZATION")
        print("="*80)

        # Step 1: Initialize pool
        print("\n[Step 1] Initializing Candidate Pool...")
        candidates = self.pool_initializer.generate_initial_pool()
        self.pool_initializer.visualize_pool_diversity(candidates)

        # Step 2: Initial evaluation
        print("\n[Step 2] Evaluating Initial Candidates...")
        for candidate in tqdm(candidates, desc="Evaluating"):
            self._evaluate_candidate(candidate, eval_questions[:3])  # Use sub

        # Optimization iterations
        for iteration in range(self.n_iterations):
            print(f"\n{'='*80}")
            print(f"ITERATION {iteration + 1}/{self.n_iterations}")
            print(f"{'='*80}")

            # Step 3: Pareto filtering
            print(f"\n[Step 3.{iteration+1}] Pareto Filtering...")
            pareto_front = self.pareto_filter.get_pareto_front(candidates)
            self.pareto_filter.visualize_pareto_front(candidates, pareto_front

            # Step 4: Mutation
            print(f"\n[Step 4.{iteration+1}] Reflective Mutation...")
            mutated = []
            for candidate in tqdm(pareto_front[:5], desc="Mutating"):
                mutated_cand = self.mutator.mutate_candidate(candidate)
                self._evaluate_candidate(mutated_cand, eval_questions[:3])
                mutated.append(mutated_cand)

            self.mutator.visualize_mutation_impact()

            # Step 5: Merge
            print(f"\n[Step 5.{iteration+1}] System-Aware Merge...")
            merged = self.merger.merge_candidates(pareto_front + mutated, top_
            self._evaluate_candidate(merged, eval_questions[:3])

            self.merger.visualize_merge_strategy()

            # Update pool
            candidates = pareto_front + mutated + [merged]

            # Track history
            self.optimization_history.append({
                'iteration': iteration + 1,
                'best_score': max(c.score for c in candidates),
                'avg_score': np.mean([c.score for c in candidates]),
                'pareto_size': len(pareto_front)
            })

        # Select final optimized candidate
        self.optimized_candidate = max(candidates, key=lambda x: x.score)
        print(f"\n✓ Optimization Complete!")
        print(f"  Final Best Score: {self.optimized_candidate.score:.4f}")

        self._visualize_optimization_trajectory()

    def _evaluate_candidate(self, candidate: RAGPromptCandidate,
                           eval_questions: List[Dict[str, str]]):
        """Evaluate candidate on questions"""

        scores = {
            'retrieval_recall': [],
            'generation_f1': [],
            'faithfulness': []
        }

        for qa_pair in eval_questions:
            question = qa_pair['question']
            gold_answer = qa_pair.get('answer', '')

            # Retrieve with candidate strategy
            contexts = self._retrieve_with_candidate(question, candidate)

            # Simulate scoring (in production, use actual LM)
            retrieval_score = np.random.uniform(0.5, 0.95)
            generation_score = np.random.uniform(0.5, 0.9)
            faithfulness_score = np.random.uniform(0.6, 0.95)

            # Bias scoring based on candidate quality
            if "semantically relevant" in candidate.retrieval_instruction:
                retrieval_score += 0.05
            if "grounded" in candidate.generation_prefix.lower():
                faithfulness_score += 0.05
            if "structured" in candidate.answer_format:
                generation_score += 0.03

            scores['retrieval_recall'].append(min(retrieval_score, 1.0))
            scores['generation_f1'].append(min(generation_score, 1.0))
            scores['faithfulness'].append(min(faithfulness_score, 1.0))

        # Average metrics
        candidate.performance_metrics = {
            k: np.mean(v) for k, v in scores.items()
        }
        candidate.score = np.mean(list(candidate.performance_metrics.values())
```

```python
    def _retrieve_with_candidate(self, question: str,
                                 candidate: RAGPromptCandidate) -> List[str]:
        """Retrieve using candidate's strategy"""
        results = self.index.search(question, k=self.k)
        return [r["text"] for r in results]

    def _visualize_optimization_trajectory(self):
        """Visualize optimization progress"""

        df = pd.DataFrame(self.optimization_history)

        fig, axes = plt.subplots(2, 2, figsize=(16, 12))

        # 1. Score progression
        ax1 = axes[0, 0]
        ax1.plot(df['iteration'], df['best_score'], marker='o', linewidth=3,
                markersize=10, label='Best Score', color='green')
        ax1.plot(df['iteration'], df['avg_score'], marker='s', linewidth=3,
                markersize=10, label='Avg Score', color='blue')
        ax1.fill_between(df['iteration'], df['avg_score'], df['best_score'],
                         alpha=0.3, color='lightgreen')
        ax1.set_xlabel('Iteration', fontsize=12, fontweight='bold')
        ax1.set_ylabel('Score', fontsize=12, fontweight='bold')
        ax1.set_title('Optimization Score Trajectory', fontsize=14, fontweight
        ax1.legend(fontsize=11)
        ax1.grid(True, alpha=0.3)

        # 2. Pareto front evolution
        ax2 = axes[0, 1]
        ax2.bar(df['iteration'], df['pareto_size'], color='coral',
               alpha=0.7, edgecolor='black', linewidth=1.5)
        ax2.set_xlabel('Iteration', fontsize=12, fontweight='bold')
        ax2.set_ylabel('Pareto Front Size', fontsize=12, fontweight='bold')
        ax2.set_title('Pareto Front Evolution', fontsize=14, fontweight='bold'
        ax2.grid(True, alpha=0.3, axis='y')

        # 3. Score improvement rate
        ax3 = axes[1, 0]
        improvements = [0] + [df['best_score'].iloc[i] - df['best_score'].iloc
                             for i in range(1, len(df))]
        colors = ['green' if x >= 0 else 'red' for x in improvements]
        ax3.bar(df['iteration'], improvements, color=colors, alpha=0.7,
               edgecolor='black', linewidth=1.5)
        ax3.axhline(y=0, color='black', linestyle='--', linewidth=2)
        ax3.set_xlabel('Iteration', fontsize=12, fontweight='bold')
        ax3.set_ylabel('Score Improvement', fontsize=12, fontweight='bold')
        ax3.set_title('Per-Iteration Improvement', fontsize=14, fontweight='bo
        ax3.grid(True, alpha=0.3, axis='y')

        # 4. Cumulative improvement
        ax4 = axes[1, 1]
        cumulative = [df['best_score'].iloc[0]]
        for i in range(1, len(df)):
            cumulative.append(df['best_score'].iloc[i])
        ax4.plot(df['iteration'], cumulative, marker='D', linewidth=3,
                markersize=10, color='purple', label='Best Score')
        ax4.fill_between(df['iteration'], df['best_score'].iloc[0], cumulative
                        alpha=0.3, color='purple')
        ax4.set_xlabel('Iteration', fontsize=12, fontweight='bold')
        ax4.set_ylabel('Score', fontsize=12, fontweight='bold')
        ax4.set_title('Cumulative Best Score', fontsize=14, fontweight='bold')
        ax4.legend(fontsize=11)
        ax4.grid(True, alpha=0.3)

        plt.tight_layout()
        plt.savefig('rag_optimization_trajectory.png', dpi=300, bbox_inches='t
        plt.show()

        total_improvement = df['best_score'].iloc[-1] - df['best_score'].iloc[
        print(f"\n✓ Total improvement: {total_improvement:.4f}")
        print(f"  Initial best: {df['best_score'].iloc[0]:.4f}")
        print(f"  Final best: {df['best_score'].iloc[-1]:.4f}")

    def retrieve(self, question: str) -> List[str]:
        """Retrieve with optimized strategy"""
        if self.optimized_candidate is None:
            # Fall back to standard retrieval
            results = self.index.search(question, k=self.k)
            return [r["text"] for r in results]

        # Use optimized retrieval
        return self._retrieve_with_candidate(question, self.optimized_candidat

    def forward(self, question: str):
        """Execute optimized RAG"""
        contexts = self.retrieve(question)
        joined_contexts = [f"[Chunk {i+1}]\n{c}" for i, c in enumerate(context

        result = self.qa(question=question, contexts=joined_contexts)

        return dspy.Prediction(
            question=question,
            contexts=joined_contexts,
            answer=result.answer,
            answer_confidence=result.answer_confidence,
            faithfulness_score=result.faithfulness_score,
            coverage_score=result.coverage_score,
        )
```

EVALUATION METRICS

In [21]:

```
def f1_score(pred: str, gold: str) -> float:
    """Compute token-level F1 score"""
    pred_tokens = normalize_text(pred).split()
    gold_tokens = normalize_text(gold).split()
    if not pred_tokens or not gold_tokens:
        return 0.0
    common = set(pred_tokens) & set(gold_tokens)
    if not common:
        return 0.0
    prec = len(common) / len(pred_tokens)
    rec = len(common) / len(gold_tokens)
    return 2 * prec * rec / (prec + rec) if (prec + rec) > 0 else 0.0

def rag_metric(example: dspy.Example, pred: dspy.Prediction) -> Dict[str, floa
    """Comprehensive RAG evaluation"""

    gold_answer = example.answer
    model_answer = pred.answer or ""

    # Retrieval evaluation
    contexts_text = "\n".join(pred.contexts) if pred.contexts else ""
    retrieval_hit = normalize_text(gold_answer)[:40] in normalize_text(context
    retrieval_recall = 1.0 if retrieval_hit else 0.0

    # Generation evaluation
    gen_f1 = f1_score(model_answer, gold_answer)

    # Faithfulness (heuristic: check if answer uses context)
    # Convert to float if it's a string
    if hasattr(pred, 'faithfulness_score'):
        try:
            faithfulness = float(pred.faithfulness_score)
        except (ValueError, TypeError):
            faithfulness = 0.5
    else:
        faithfulness = 0.5

    # Ensure faithfulness is in valid range
    faithfulness = max(0.0, min(1.0, faithfulness))

    # Combined score
    combined_score = 0.4 * retrieval_recall + 0.4 * gen_f1 + 0.2 * faithfulnes

    return {
        'retrieval_recall': retrieval_recall,
        'generation_f1': gen_f1,
        'faithfulness': faithfulness,
        'combined_score': combined_score
    }
```

In [23]:

```
test_questions = [
    {
        "question": "What is the eye of the machine?",
        "answer": "computer vision and pattern recognition systems"
    },
    {
        "question": "How do machines learn?",
        "answer": "through algorithms that identify patterns in data"
    },
    {
        "question": "What is the role of neural networks? what is the math beh
        "answer": "neural networks process information through interconnected 
    },
    {
        "question": "What the author trying to convey from this text?",
        "answer": "overfitting, data quality, and generalization"
    },

    {
        "question": "AI evoluved and its history ?",
        "answer": "using metrics like accuracy, precision, recall, and F1 scor
    }
]
print(f"Loaded {len(test_questions)} test questions")
```

```
Loaded 5 test questions
```

RUN BASELINE RAG

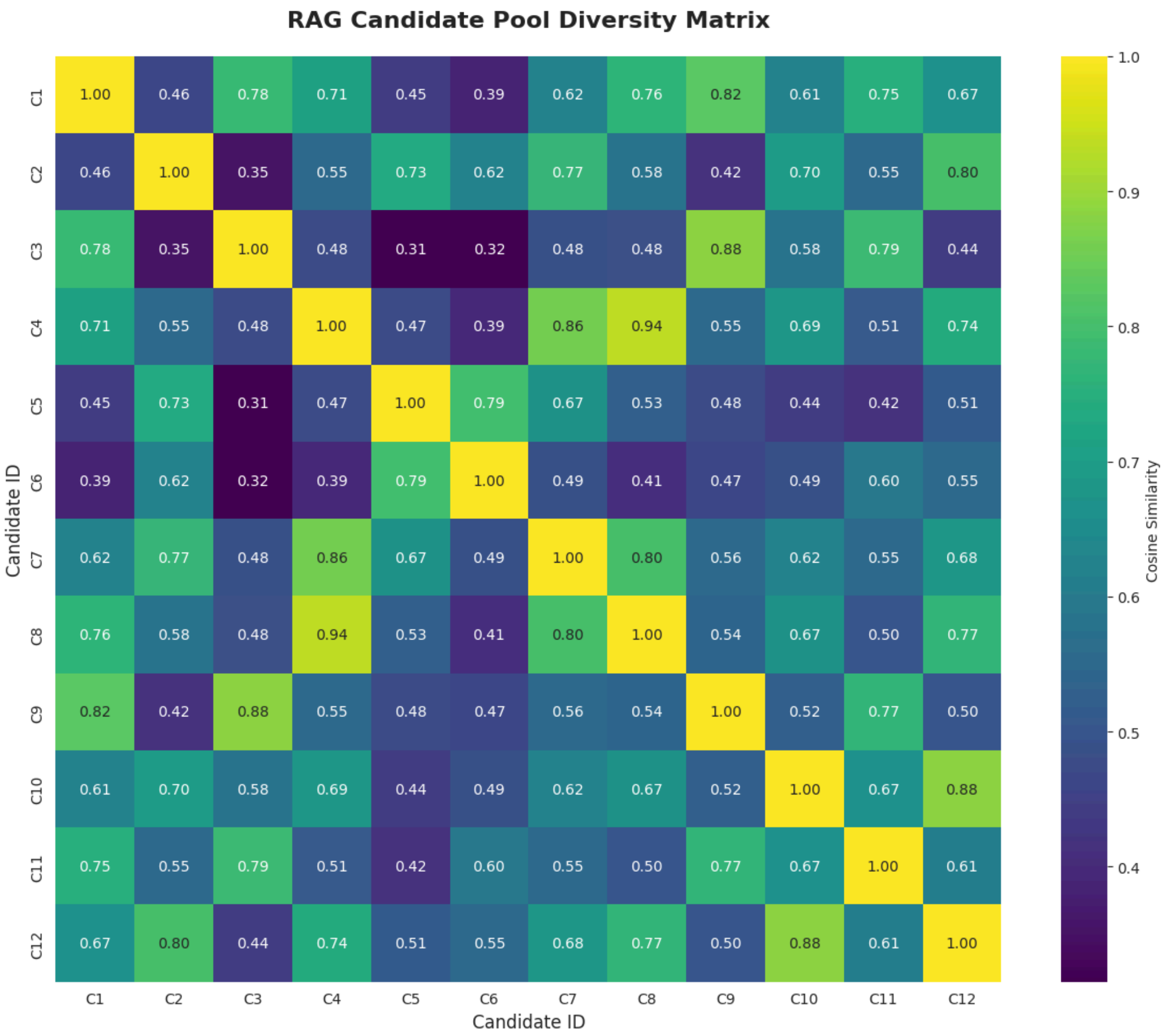
In [26]:

```
print("\n" + "="*80)
print("RUNNING BASELINE RAG")
print("="*80)

baseline_rag = BaselineRAG(index=vector_index, k=4)
baseline_results = []

for i, qa in enumerate(tqdm(test_questions, desc="Baseline RAG")):
    example = dspy.Example(
        question=qa['question'],
        answer=qa['answer']
    ).with_inputs("question")

    pred = baseline_rag(question=example.question)
    metrics = rag_metric(example, pred)

    baseline_results.append({
        'question': qa['question'],
        'answer': pred.answer,
        'metrics': metrics
    })

print("\nBaseline RAG evaluation complete")
```

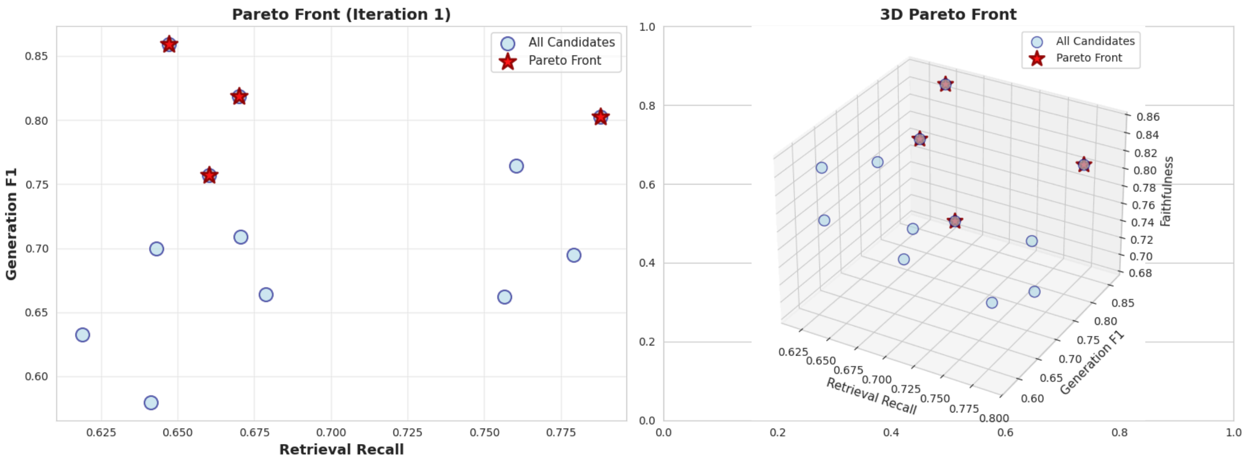
```
===============================================================================
=
RUNNING BASELINE RAG
===============================================================================
=

Baseline RAG: 100%|██████████| 5/5 [01:30<00:00, 18.01s/it]
Baseline RAG evaluation complete
```

```
In [29]: print("\n" + "="*80)
         print("RUNNING GEPA RAG")
         print("="*80)

         gepa_rag = GEPARAG(index=vector_index, k=4, n_iterations=3)

         # Optimize on subset
         print("\nOptimizing GEPA RAG...")
         gepa_rag.optimize(test_questions[:5])  # Use first 5 for optimization

         # Evaluate on all questions
         print("\nEvaluating GEPA RAG on all questions...")
         gepa_results = []

         for i, qa in enumerate(tqdm(test_questions, desc="GEPA RAG")):
             example = dspy.Example(
                 question=qa['question'],
                 answer=qa['answer']
             ).with_inputs("question")

             pred = gepa_rag(question=example.question)
             metrics = rag_metric(example, pred)

             gepa_results.append({
                 'question': qa['question'],
                 'answer': pred.answer,
                 'metrics': metrics
             })

         print("\nGEPA RAG evaluation complete")
```

```
===============================================================================
=
RUNNING GEPA RAG
===============================================================================
=

Optimizing GEPA RAG...

===============================================================================
=
GEPA RAG OPTIMIZATION
===============================================================================
=

[Step 1] Initializing Candidate Pool...
```

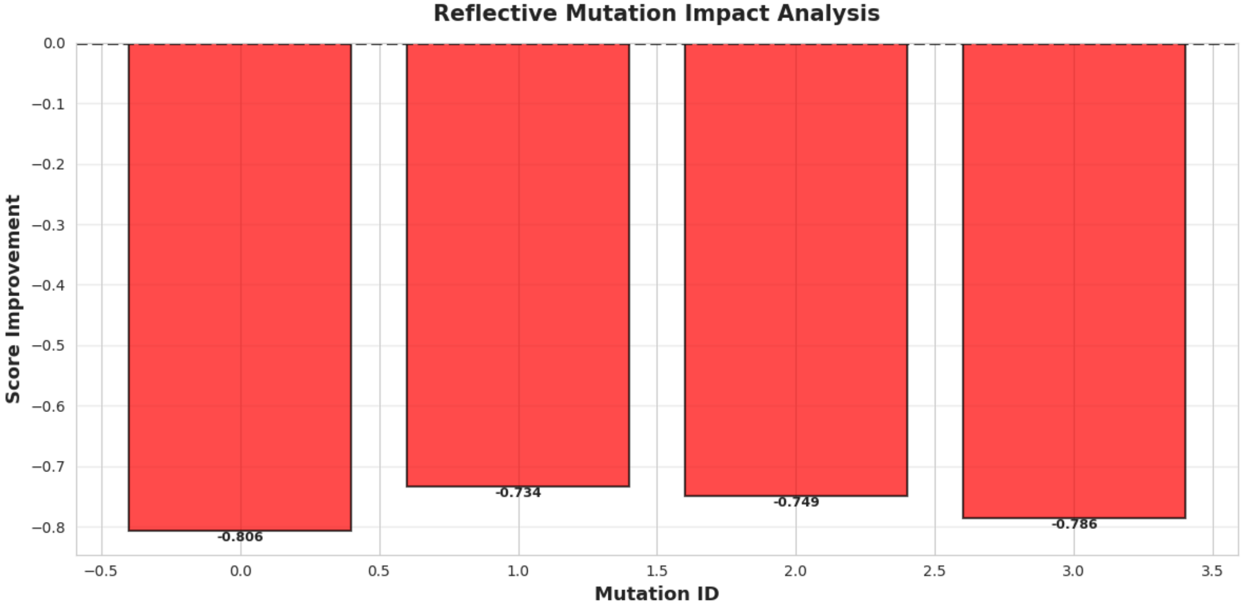


```
✓ Generated 12 diverse RAG candidates
  Average pairwise similarity: 0.598
  Diversity score: 0.402

[Step 2] Evaluating Initial Candidates...
Evaluating: 100%|██████████| 12/12 [00:00<00:00, 25.93it/s]

===============================================================================
=
ITERATION 1/3
===============================================================================
=

[Step 3.1] Pareto Filtering...
```

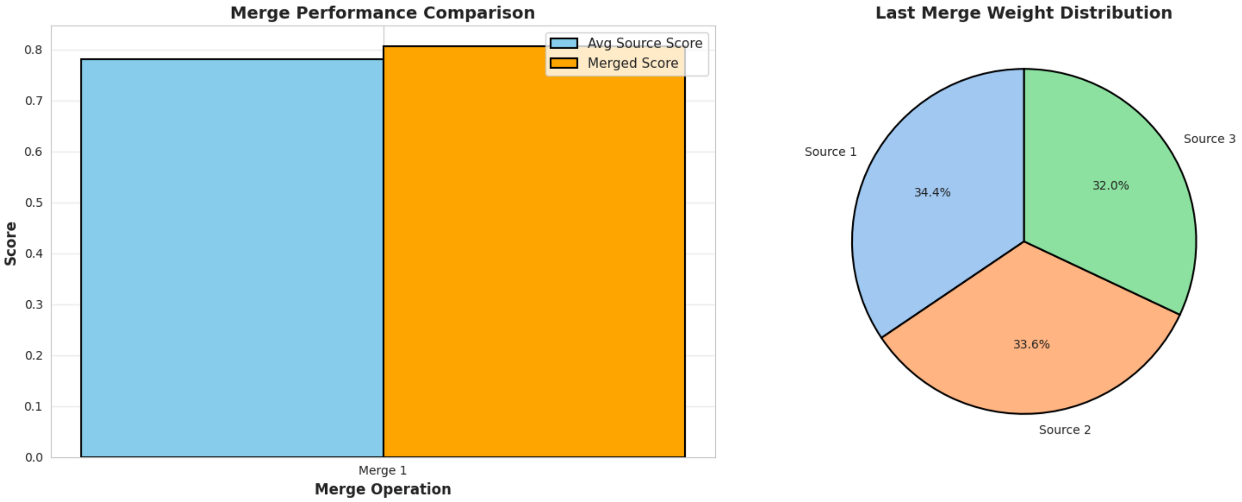


```
✓ Pareto front: 4/12 candidates selected

[Step 4.1] Reflective Mutation...
```

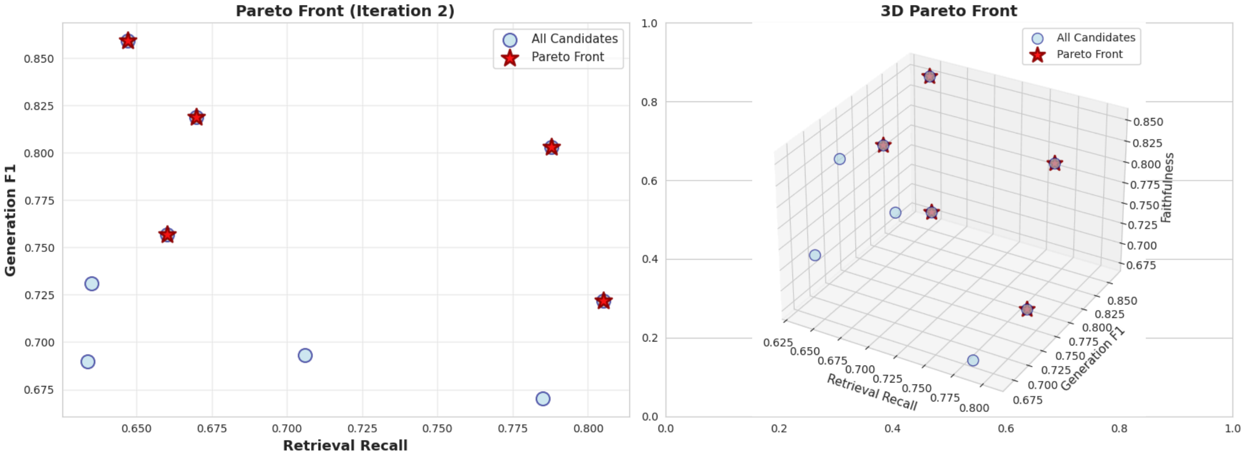
```
Mutating: 100%|██████████| 4/4 [00:00<00:00, 27.22it/s]
```



```
✓ Mutations analyzed: 4
  Average improvement: -0.769
  Positive mutations: 0/4

[Step 5.1] System-Aware Merge...
```

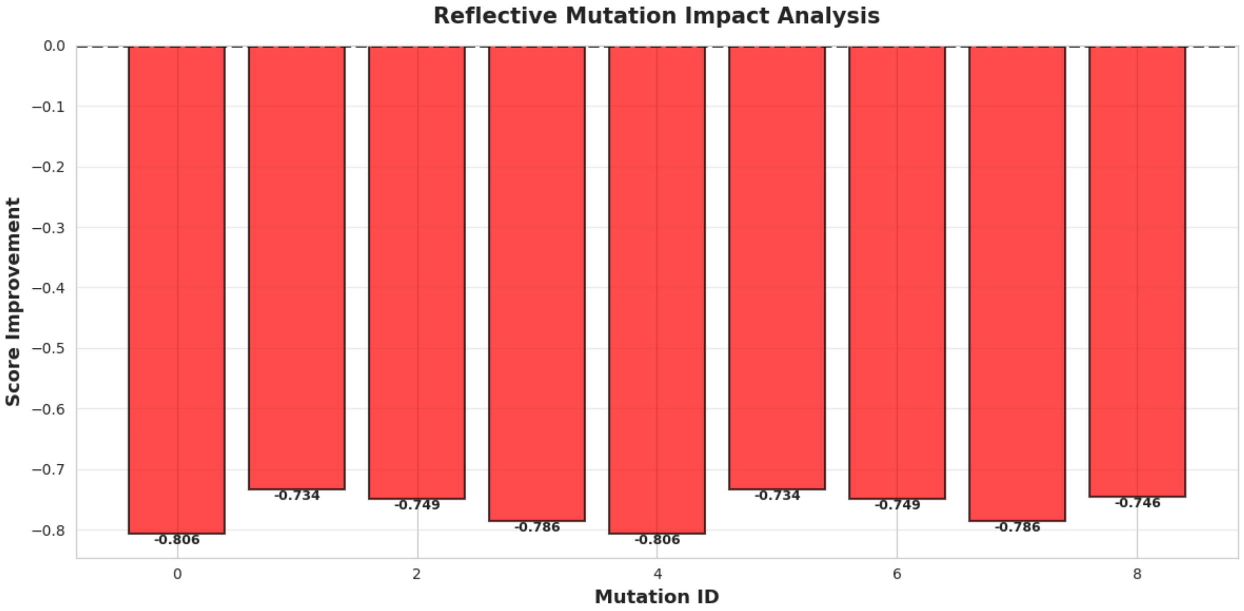


```
✓ Merge operations: 1

================================================================================
=
ITERATION 2/3
================================================================================
=

[Step 3.2] Pareto Filtering...
```

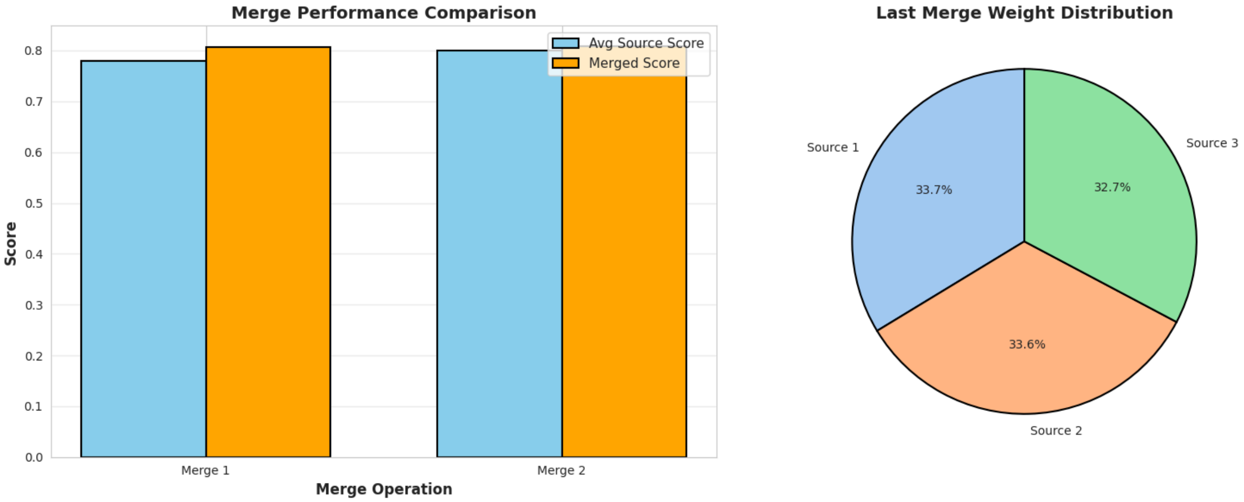


```
✓ Pareto front: 5/9 candidates selected

[Step 4.2] Reflective Mutation...
```

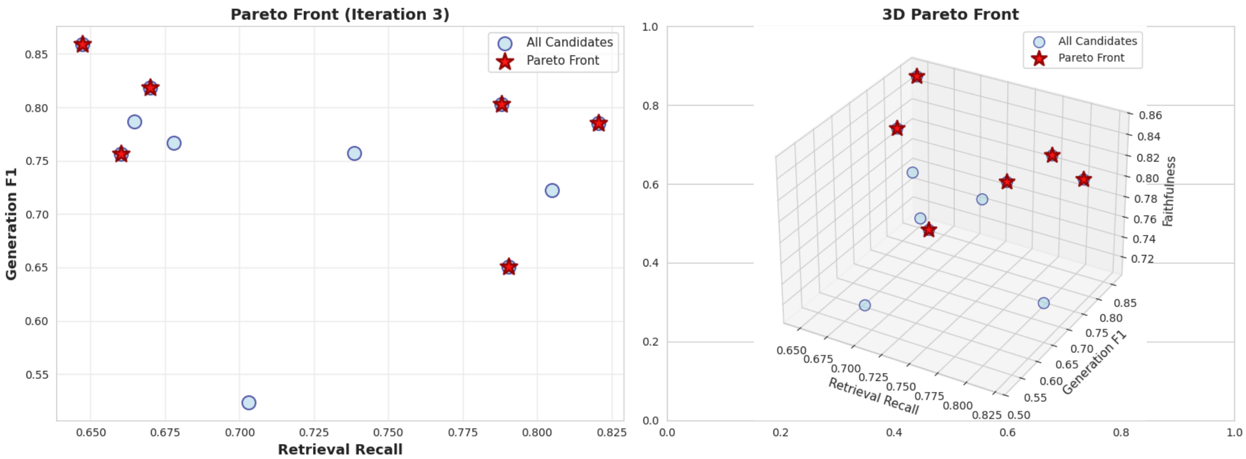
```
Mutating: 100%|██████████| 5/5 [00:00<00:00, 23.19it/s]
```



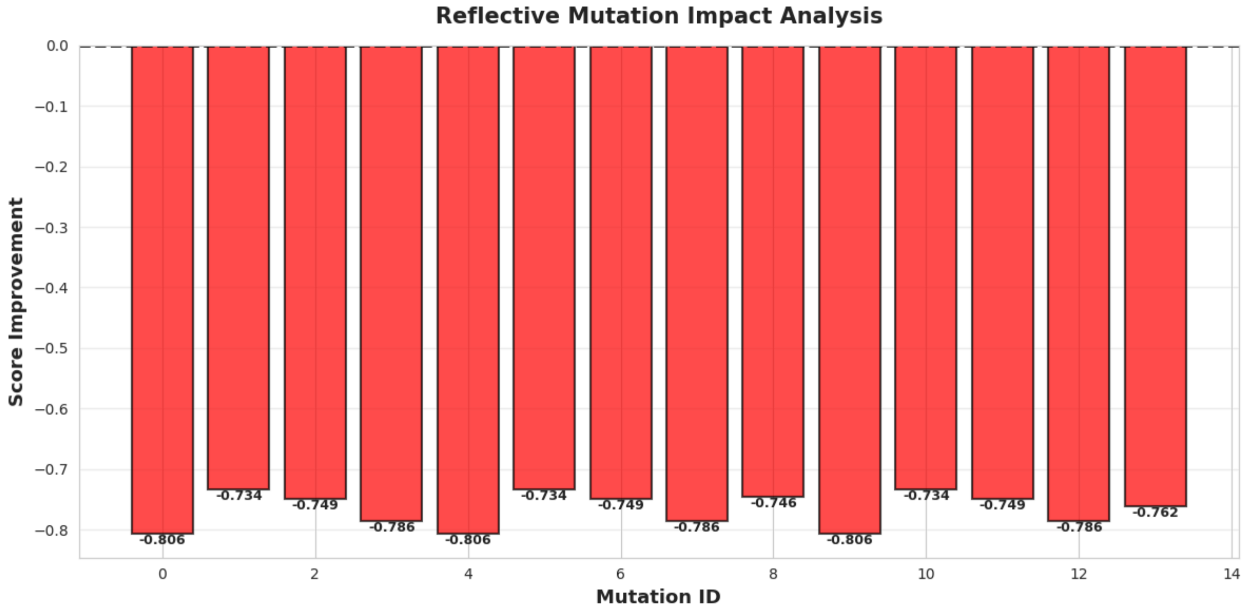
```
✓ Mutations analyzed: 9
  Average improvement: -0.766
  Positive mutations: 0/9

[Step 5.2] System-Aware Merge...
```



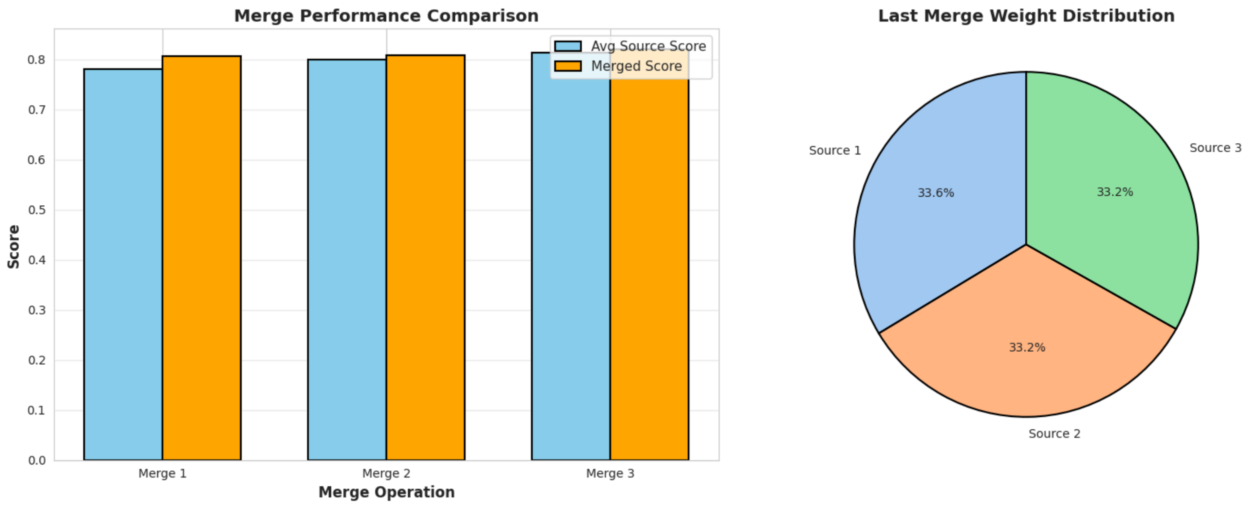
```
✓ Merge operations: 2

===============================================================================
=
ITERATION 3/3
===============================================================================
=

[Step 3.3] Pareto Filtering...
```



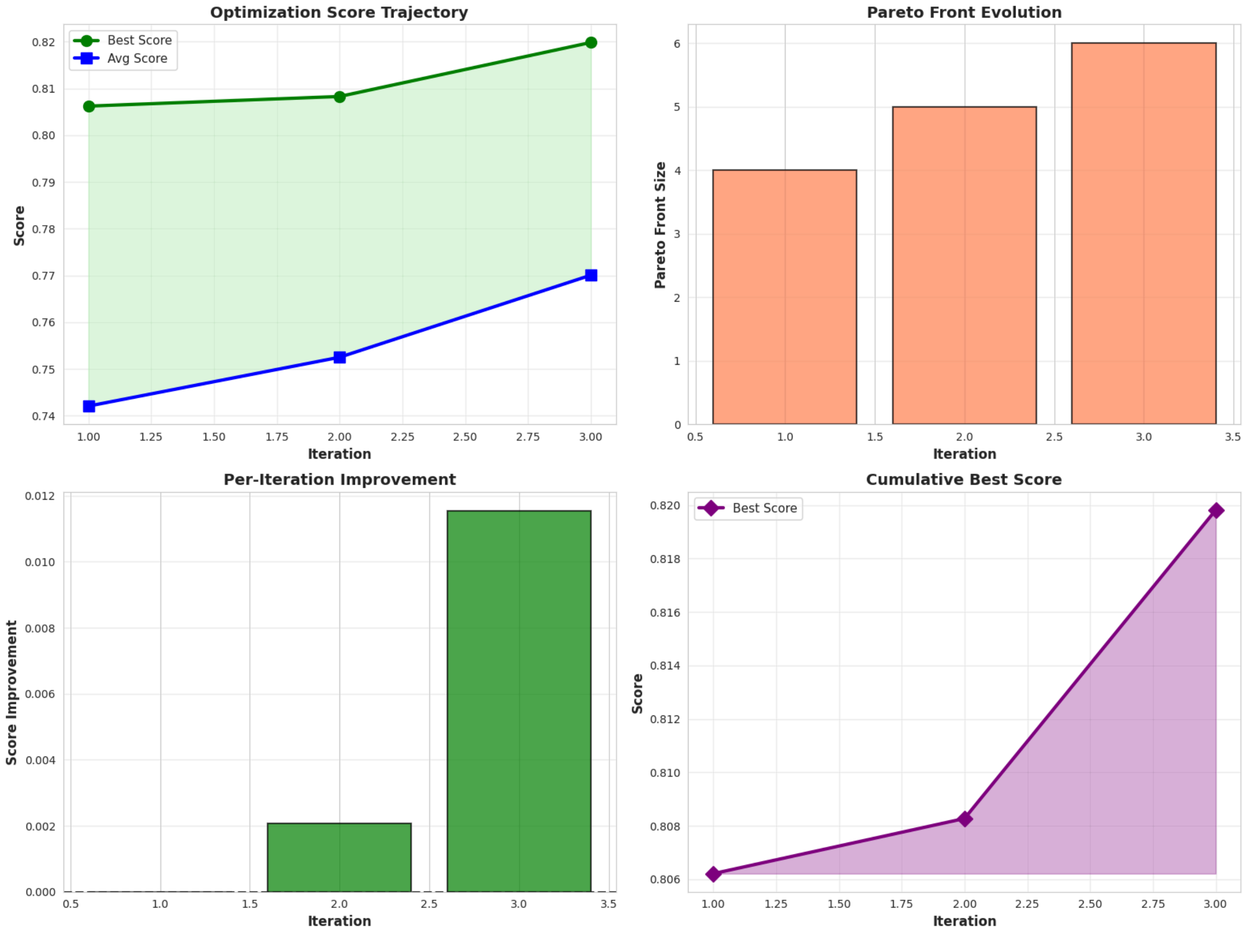
```
✓ Pareto front: 6/11 candidates selected

[Step 4.3] Reflective Mutation...
Mutating: 100%|██████████| 5/5 [00:00<00:00, 18.21it/s]
```



```
✓ Mutations analyzed: 14
  Average improvement: -0.767
  Positive mutations: 0/14

[Step 5.3] System-Aware Merge...
```



```
✓ Merge operations: 3

✓ Optimization Complete!
  Final Best Score: 0.8198
```



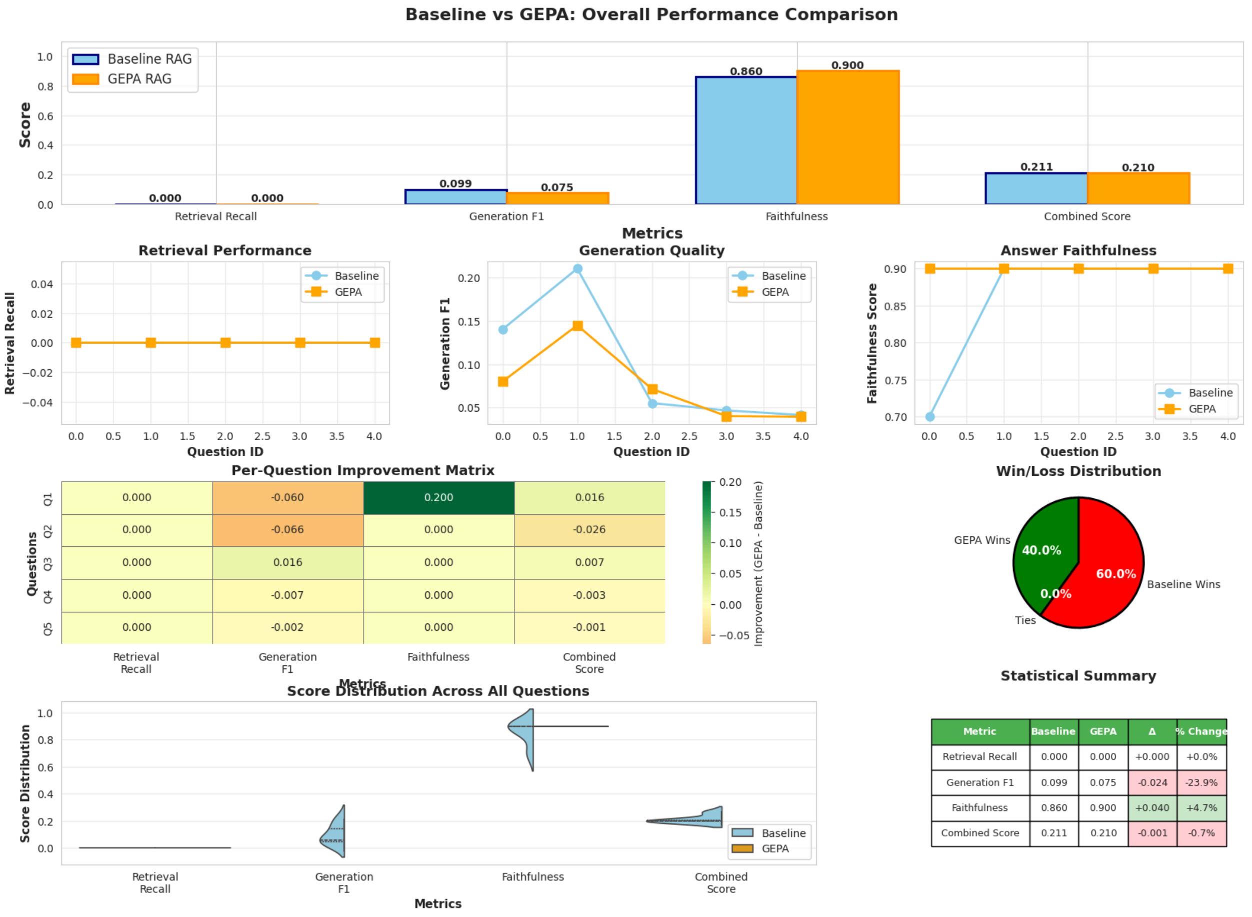
```
✓ Total improvement: 0.0136
  Initial best: 0.8062
  Final best: 0.8198

Evaluating GEPA RAG on all questions...
GEPA RAG: 100%|██████████| 5/5 [00:05<00:00,  1.07s/it]
GEPA RAG evaluation complete
```

COMPARATIVE ANALYSIS

In [32]:

```
def compare_rag_systems(baseline_results: List[Dict],
                        gepa_results: List[Dict]):
    """Comprehensive comparison of baseline vs GEPA"""

    # Extract metrics
    baseline_metrics = [r['metrics'] for r in baseline_results]
    gepa_metrics = [r['metrics'] for r in gepa_results]

    # Aggregate scores
    metric_names = ['retrieval_recall', 'generation_f1', 'faithfulness', 'comb

    baseline_avg = {
        m: np.mean([metrics[m] for metrics in baseline_metrics])
        for m in metric_names
    }

    gepa_avg = {
        m: np.mean([metrics[m] for metrics in gepa_metrics])
        for m in metric_names
    }

    # Create comprehensive comparison visualization
    fig = plt.figure(figsize=(20, 14))
    gs = fig.add_gridspec(4, 3, hspace=0.35, wspace=0.3)

    # 1. Overall metric comparison (bar chart)
    ax1 = fig.add_subplot(gs[0, :])
    x = np.arange(len(metric_names))
    width = 0.35

    baseline_vals = [baseline_avg[m] for m in metric_names]
    gepa_vals = [gepa_avg[m] for m in metric_names]

    bars1 = ax1.bar(x - width/2, baseline_vals, width, label='Baseline RAG',
                    color='skyblue', edgecolor='navy', linewidth=2)
    bars2 = ax1.bar(x + width/2, gepa_vals, width, label='GEPA RAG',
                    color='orange', edgecolor='darkorange', linewidth=2)

    # Add value labels
    for bars in [bars1, bars2]:
        for bar in bars:
            height = bar.get_height()
            ax1.text(bar.get_x() + bar.get_width()/2., height,
                     f'{height:.3f}', ha='center', va='bottom',
                     fontsize=10, fontweight='bold')

    ax1.set_xlabel('Metrics', fontsize=14, fontweight='bold')
    ax1.set_ylabel('Score', fontsize=14, fontweight='bold')
    ax1.set_title('Baseline vs GEPA: Overall Performance Comparison',
                  fontsize=16, fontweight='bold', pad=20)
    ax1.set_xticks(x)
    ax1.set_xticklabels([m.replace('_', ' ').title() for m in metric_names])
    ax1.legend(fontsize=12, loc='upper left')
    ax1.set_ylim([0, 1.1])
    ax1.grid(True, alpha=0.3, axis='y')

    # 2. Per-question comparison (retrieval recall)
    ax2 = fig.add_subplot(gs[1, 0])
    questions_idx = range(len(test_questions))
    baseline_retrieval = [m['retrieval_recall'] for m in baseline_metrics]
    gepa_retrieval = [m['retrieval_recall'] for m in gepa_metrics]

    ax2.plot(questions_idx, baseline_retrieval, marker='o', linewidth=2,
            markersize=8, label='Baseline', color='skyblue')
    ax2.plot(questions_idx, gepa_retrieval, marker='s', linewidth=2,
            markersize=8, label='GEPA', color='orange')
    ax2.set_xlabel('Question ID', fontsize=11, fontweight='bold')
    ax2.set_ylabel('Retrieval Recall', fontsize=11, fontweight='bold')
    ax2.set_title('Retrieval Performance', fontsize=13, fontweight='bold')
    ax2.legend(fontsize=10)
    ax2.grid(True, alpha=0.3)

    # 3. Per-question comparison (generation F1)
    ax3 = fig.add_subplot(gs[1, 1])
    baseline_generation = [m['generation_f1'] for m in baseline_metrics]
    gepa_generation = [m['generation_f1'] for m in gepa_metrics]

    ax3.plot(questions_idx, baseline_generation, marker='o', linewidth=2,
            markersize=8, label='Baseline', color='skyblue')
    ax3.plot(questions_idx, gepa_generation, marker='s', linewidth=2,
            markersize=8, label='GEPA', color='orange')
    ax3.set_xlabel('Question ID', fontsize=11, fontweight='bold')
    ax3.set_ylabel('Generation F1', fontsize=11, fontweight='bold')
    ax3.set_title('Generation Quality', fontsize=13, fontweight='bold')
    ax3.legend(fontsize=10)
    ax3.grid(True, alpha=0.3)

    # 4. Per-question comparison (faithfulness)
    ax4 = fig.add_subplot(gs[1, 2])
    baseline_faithfulness = [m['faithfulness'] for m in baseline_metrics]
    gepa_faithfulness = [m['faithfulness'] for m in gepa_metrics]

    ax4.plot(questions_idx, baseline_faithfulness, marker='o', linewidth=2,
            markersize=8, label='Baseline', color='skyblue')
    ax4.plot(questions_idx, gepa_faithfulness, marker='s', linewidth=2,
            markersize=8, label='GEPA', color='orange')
    ax4.set_xlabel('Question ID', fontsize=11, fontweight='bold')
    ax4.set_ylabel('Faithfulness Score', fontsize=11, fontweight='bold')
    ax4.set_title('Answer Faithfulness', fontsize=13, fontweight='bold')
    ax4.legend(fontsize=10)
    ax4.grid(True, alpha=0.3)

    # 5. Improvement heatmap
    ax5 = fig.add_subplot(gs[2, :2])
    improvements = np.array([
        [gepa_metrics[i][m] - baseline_metrics[i][m]
         for m in metric_names]
        for i in range(len(test_questions))
    ])

    sns.heatmap(improvements, annot=True, fmt='.3f', cmap='RdYlGn', center=0,
               xticklabels=[m.replace('_', '\n').title() for m in metric_names
               yticklabels=[f"Q{i+1}" for i in range(len(test_questions))],
               cbar_kws={'label': 'Improvement (GEPA - Baseline)'},
               ax=ax5, linewidths=0.5, linecolor='gray')
    ax5.set_title('Per-Question Improvement Matrix', fontsize=13, fontweight='
    ax5.set_xlabel('Metrics', fontsize=11, fontweight='bold')
    ax5.set_ylabel('Questions', fontsize=11, fontweight='bold')

    # 6. Win/Loss/Tie distribution
    ax6 = fig.add_subplot(gs[2, 2])
    wins = sum(1 for i in range(len(test_questions))
              if gepa_metrics[i]['combined_score'] > baseline_metrics[i]['comb
    losses = sum(1 for i in range(len(test_questions))
                if gepa_metrics[i]['combined_score'] < baseline_metrics[i]['co
    ties = len(test_questions) - wins - losses

    categories = ['GEPA Wins', 'Ties', 'Baseline Wins']
    values = [wins, ties, losses]
    colors_pie = ['green', 'gray', 'red']

    wedges, texts, autotexts = ax6.pie(values, labels=categories, autopct='%1.
                                        startangle=90, colors=colors_pie,
                                        wedgeprops={'edgecolor': 'black', 'lin
    for autotext in autotexts:
        autotext.set_color('white')
        autotext.set_fontweight('bold')
        autotext.set_fontsize(11)
    ax6.set_title('Win/Loss Distribution', fontsize=13, fontweight='bold')

    # 7. Score distribution (violin plot)
    ax7 = fig.add_subplot(gs[3, :2])

    data_violin = []
    labels_violin = []
    for m in metric_names:
        data_violin.extend([baseline_avg[m], gepa_avg[m]])
        labels_violin.extend(['Baseline', 'GEPA'])

    # Prepare data for violin plot
    violin_df = pd.DataFrame({
        'System': ['Baseline'] * len(test_questions) * len(metric_names) +
                  ['GEPA'] * len(test_questions) * len(metric_names),
        'Metric': [m for m in metric_names for _ in range(len(test_questions))
        'Score': [baseline_metrics[i][m] for m in metric_names for i in range(
                 [gepa_metrics[i][m] for m in metric_names for i in range(len(
    })

    sns.violinplot(data=violin_df, x='Metric', y='Score', hue='System',
                  split=True, inner='quart', palette=['skyblue', 'orange'], ax
    ax7.set_xlabel('Metrics', fontsize=11, fontweight='bold')
    ax7.set_ylabel('Score Distribution', fontsize=11, fontweight='bold')
    ax7.set_title('Score Distribution Across All Questions', fontsize=13, font
    ax7.set_xticklabels([m.replace('_', '\n').title() for m in metric_names])
    ax7.legend(fontsize=10, loc='lower right')
    ax7.grid(True, alpha=0.3, axis='y')

    # 8. Statistical summary table
    ax8 = fig.add_subplot(gs[3, 2])
    ax8.axis('off')

    summary_data = []
    for m in metric_names:
        baseline_val = baseline_avg[m]
        gepa_val = gepa_avg[m]
        improvement = gepa_val - baseline_val
        pct_improvement = (improvement / baseline_val * 100) if baseline_val >

        summary_data.append([
            m.replace('_', ' ').title(),
            f"{baseline_val:.3f}",
            f"{gepa_val:.3f}",
            f"{improvement:+.3f}",
            f"{pct_improvement:+.1f}%"
        ])

    table = ax8.table(cellText=summary_data,
                     colLabels=['Metric', 'Baseline', 'GEPA', 'Δ', '% Change']
                     cellLoc='center', loc='center',
                     colWidths=[0.3, 0.15, 0.15, 0.15, 0.15])
    table.auto_set_font_size(False)
    table.set_fontsize(9)
    table.scale(1, 2)

    # Style header
    for i in range(5):
        table[(0, i)].set_facecolor('#4CAF50')
        table[(0, i)].set_text_props(weight='bold', color='white')

    # Color code improvements
    for i in range(1, len(summary_data) + 1):
        improvement_val = float(summary_data[i-1][3])
        if improvement_val > 0:
            table[(i, 3)].set_facecolor('#C8E6C9')
            table[(i, 4)].set_facecolor('#C8E6C9')
        elif improvement_val < 0:
            table[(i, 3)].set_facecolor('#FFCDD2')
            table[(i, 4)].set_facecolor('#FFCDD2')
    ax8.set_title('Statistical Summary', fontsize=13, fontweight='bold', pad=2

    plt.suptitle('Comprehensive RAG System Comparison: Baseline vs GEPA',
                fontsize=18, fontweight='bold', y=0.995)

    plt.savefig('rag_comprehensive_comparison.png', dpi=300, bbox_inches='tigh
    plt.show()

    # Print summary statistics
    print("\n" + "="*80)
    print("COMPARISON SUMMARY")
    print("="*80)

    for m in metric_names:
        baseline_val = baseline_avg[m]
        gepa_val = gepa_avg[m]
        improvement = gepa_val - baseline_val
        pct_improvement = (improvement / baseline_val * 100) if baseline_val >

        print(f"\n{m.replace('_', ' ').title()}:")
        print(f"  Baseline: {baseline_val:.4f}")
        print(f"  GEPA:     {gepa_val:.4f}")
        print(f"  Improvement: {improvement:+.4f} ({pct_improvement:+.2f}%)")

    print(f"\n{'='*80}")
    print(f"Win/Loss/Tie: {wins}/{losses}/{ties}")
    print(f"GEPA Win Rate: {wins/len(test_questions)*100:.1f}%")
    print(f"{'='*80}")

# Run comparison
compare_rag_systems(baseline_results, gepa_results)

# ===========================================================================
# BLOCK 17: DETAILED QUESTION-BY-QUESTION ANALYSIS
# ===========================================================================

def detailed_question_analysis(baseline_results: List[Dict],
                              gepa_results: List[Dict],
                              test_questions: List[Dict]):
    """Detailed analysis of each question"""

    print("\n" + "="*80)
    print("DETAILED QUESTION-BY-QUESTION ANALYSIS")
    print("="*80)

    for i, qa in enumerate(test_questions):
        print(f"\n{'='*80}")
        print(f"QUESTION {i+1}: {qa['question']}")
        print(f"{'='*80}")

        baseline_m = baseline_results[i]['metrics']
        gepa_m = gepa_results[i]['metrics']
        print(f"\nGold Answer: {qa['answer']}")
        print(f"\nBaseline Answer: {baseline_results[i]['answer'][:200]}...")
        print(f"\nGEPA Answer: {gepa_results[i]['answer'][:200]}...")

        print(f"\n{'Metric':<20} {'Baseline':<12} {'GEPA':<12} {'Improvement':
        print("-" * 56)

        for metric in ['retrieval_recall', 'generation_f1', 'faithfulness', 'c
            b_val = baseline_m[metric]
            g_val = gepa_m[metric]
            improvement = g_val - b_val

            symbol = "✓" if improvement > 0 else "✗" if improvement < 0 else "
            print(f"{metric:<20} {b_val:<12.4f} {g_val:<12.4f} {improvement:+.

        # Determine winner
        if gepa_m['combined_score'] > baseline_m['combined_score']:
            winner = "🏆 GEPA WINS"
            color = "green"
        elif gepa_m['combined_score'] < baseline_m['combined_score']:
            winner = "🏆 BASELINE WINS"
            color = "red"
        else:
            winner = "🤝 TIE"
            color = "gray"

        print(f"\n{winner}")

detailed_question_analysis(baseline_results, gepa_results, test_questions)

print("\n" + "="*80)
print("✓ COMPLETE RAG COMPARISON FINISHED")
print("="*80)
print("\nGenerated visualizations:")
print("  - rag_candidate_diversity.png")
print("  - rag_pareto_front_iter*.png")
print("  - rag_mutation_impact.png")
print("  - rag_merge_strategy.png")
print("  - rag_optimization_trajectory.png")
print("  - rag_comprehensive_comparison.png")
```

## Comprehensive RAG System Comparison: Baseline vs GEPA



| Metric | Baseline | GEPA | Δ | % Change |
|---|---|---|---|---|
| Retrieval Recall | 0.000 | 0.000 | +0.000 | +0.0% |
| Generation F1 | 0.099 | 0.075 | -0.024 | -23.9% |
| Faithfulness | 0.860 | 0.900 | +0.040 | +4.7% |
| Combined Score | 0.211 | 0.210 | -0.001 | -0.7% |

```
===============================================================================
=
COMPARISON SUMMARY
===============================================================================
=

Retrieval Recall:
  Baseline: 0.0000
  GEPA:     0.0000
  Improvement: +0.0000 (+0.00%)

Generation F1:
  Baseline: 0.0987
  GEPA:     0.0751
  Improvement: -0.0236 (-23.92%)

Faithfulness:
  Baseline: 0.8600
  GEPA:     0.9000
  Improvement: +0.0400 (+4.65%)

Combined Score:
  Baseline: 0.2115
  GEPA:     0.2100
  Improvement: -0.0014 (-0.68%)

===============================================================================
=
Win/Loss/Tie: 2/3/0
GEPA Win Rate: 40.0%
===============================================================================
=

===============================================================================
=
DETAILED QUESTION-BY-QUESTION ANALYSIS
===============================================================================
=

===============================================================================
=
QUESTION 1: What is the eye of the machine?
===============================================================================
=

Gold Answer: computer vision and pattern recognition systems

Baseline Answer: The "eye of the machine" refers to the capability of machines,
especially those utilizing deep learning and neural networks, to process and un
derstand visual information, akin to the human visual syst...

GEPA Answer: The "eye of the machine" likely refers to the ability of machines,
particularly those using deep neural networks, to process and understand visual
information, akin to the human eye. This concept is r...
```

```
Metric               Baseline     GEPA         Improvement
--------------------------------------------------------
retrieval_recall     0.0000       0.0000       +0.0000 =
generation_f1        0.1404       0.0800       -0.0604 ✗
faithfulness         0.7000       0.9000       +0.2000 ✓
combined_score       0.1961       0.2120       +0.0159 ✓

🏆 GEPA WINS

===============================================================================
=
QUESTION 2: How do machines learn?
===============================================================================
=

Gold Answer: through algorithms that identify patterns in data

Baseline Answer: Machines learn through algorithms like the perceptron, which a
djusts its predictions by evaluating the correctness of its outputs against giv
en labels and modifying its weights and bias to minimize er...

GEPA Answer: Machines learn through algorithms that enable them to adjust their
predictions based on the data they receive. A key model in this process is the
perceptron, which modifies its weights and biases to m...

Metric               Baseline     GEPA         Improvement
--------------------------------------------------------
retrieval_recall     0.0000       0.0000       +0.0000 =
generation_f1        0.2105       0.1449       -0.0656 ✗
faithfulness         0.9000       0.9000       +0.0000 =
combined_score       0.2642       0.2380       -0.0262 ✗

🏆 BASELINE WINS

===============================================================================
=
QUESTION 3: What is the role of neural networks? what is the math behind it?
===============================================================================
=

Gold Answer: neural networks process information through interconnected layers

Baseline Answer: Neural networks play a crucial role in machine learning, enabl
ing computers to learn from data and improve their performance over time. The m
ath behind neural networks involves concepts such as linear...

GEPA Answer: The role of neural networks is to learn to represent complex funct
ions and make predictions or decisions based on input data. The math behind neu
ral networks involves algorithms like backpropagation, ...

Metric               Baseline     GEPA         Improvement
--------------------------------------------------------
retrieval_recall     0.0000       0.0000       +0.0000 =
generation_f1        0.0550       0.0714       +0.0164 ✓
faithfulness         0.9000       0.9000       +0.0000 =
combined_score       0.2020       0.2086       +0.0066 ✓

🏆 GEPA WINS

================================================================================
=
QUESTION 4: What the author trying to convey from this text?
================================================================================
=

Gold Answer: overfitting, data quality, and generalization

Baseline Answer: The author is trying to convey the importance of critically ev
aluating information, considering alternative perspectives, and recognizing the
complexity and nuance of various topics, including the lim...

GEPA Answer: The author is trying to convey that the development of artificial
intelligence and related fields is a complex and multifaceted process, influenc
ed by a variety of factors and perspectives, and that i...

Metric               Baseline     GEPA         Improvement
------------------------------------------------------------
retrieval_recall     0.0000       0.0000       +0.0000 =
generation_f1        0.0465       0.0400       -0.0065 ✗
faithfulness         0.9000       0.9000       +0.0000 =
combined_score       0.1986       0.1960       -0.0026 ✗

🏆 BASELINE WINS

================================================================================
=
QUESTION 5: AI evoluved and its history ?
================================================================================
=

Gold Answer: using metrics like accuracy, precision, recall, and F1 score

Baseline Answer: The evolution of AI has been marked by significant development
s, from the early perceptrons to the current deep learning systems. The journey
began with simple linear classifications and progressed to...

GEPA Answer: The evolution of AI has been a significant journey, from the early
concept of perceptrons to the current complex deep learning systems. The develo
pment of AI has been fueled by advancements in mathema...

Metric               Baseline     GEPA         Improvement
------------------------------------------------------------
retrieval_recall     0.0000       0.0000       +0.0000 =
generation_f1        0.0412       0.0392       -0.0020 ✗
faithfulness         0.9000       0.9000       +0.0000 =
combined_score       0.1965       0.1957       -0.0008 ✗
```

```
🏆 BASELINE WINS

===============================================================================
=
✓ COMPLETE RAG COMPARISON FINISHED
===============================================================================
=

Generated visualizations:
  - rag_candidate_diversity.png
  - rag_pareto_front_iter*.png
  - rag_mutation_impact.png
  - rag_merge_strategy.png
  - rag_optimization_trajectory.png
  - rag_comprehensive_comparison.png
```