

# CIIR@LiveRAG 2025：通过自训练优化多代理检索增强生成

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## Abstract

本文介绍了 mRAG，这是一种多代理检索增强生成（RAG）框架，由专门代理组成，用于计划、搜索、推理和协调等子任务。我们的系统采用自训练范式，通过奖励引导的轨迹采样优化代理间的协作并增强响应生成。在 SIGIR 2025 LiveRAG 比赛期间对 DataMorgana 衍生的数据集进行评估，mRAG 优于传统 RAG 基准。我们进一步分析比赛结果，并通过案例研究展示该框架的优势，证明其在复杂的真实世界 RAG 任务中的有效性。

## 1 介绍

RAG 通过结合外部检索机制增强了大型语言模型（LLM），解决了诸如静态知识和缺乏当前可验证来源的基础性等限制 [1, 9, 13]。与受限于固定训练数据的传统 LLM 不同，RAG 使得从搜索引擎或数据库等来源实时访问相关文档成为可能 [14, 15]，无需重新训练即可提高准确性和相关性。最近，自主代理作为 RAG 的强大扩展出现 [8, 17]，能够进行复杂推理、工具使用和多步骤决策。其模块化设计支持动态、目标导向的信息综合，使其在需要灵活性和深度的现实世界任务中效果显著。

虽然单代理 RAG 系统有用，但它们在可扩展性、专业化和有效的上下文管理方面存在困难。单个代理同时处理多项任务——如查询制定、检索、综合和验证——可能会因上下文重叠而导致效率低下和性能下降。多代理 RAG 系统通过模块化设计解决这些问题。通过为不同的角色（例如，搜索者、策划者、总结者、验证者）分配独立的代理，每个代理在专注的上下文中操作，提高效率 and 任务一致性。代理之间的通信进一步促进了更好的任务分解和并行执行，提高了复杂推理工作流程中的鲁棒性和适应能力。

我们引入了 mRAG，一个用于构建和优化多智能体 RAG 系统的框架。该框架由一组任务专用的智能体组成，例如计划员、搜索员和推理员，每个智能体负责处理不同的子任务。一个中央协调智能体通过动态调用智能体、路由信息及监控进展来组织工作流程，以达到最终响应。协调器控制决策过程，并在产生令人满意的输出后终止工作流程。为训练智能体，我们采用一种受 Singh et al. [16] 启发的自我训练方法，为每个输入生成多样的智能体交互轨迹。通过一个奖励模型对这些轨迹进行评估，并将高奖励轨迹用作监督。智能体被训练以重现这些高奖励行为，从而在未来运行中促进有效的生成。

我们展示了在 LiveRAG<sup>1</sup> 竞赛中的实验结果，证明了所提出的多代理框架在来自该竞赛的数据生成工具 DataMorgana [3] 的数据库上表现优于传统的检索再阅读 RAG 范式。此外，我们分析了在竞赛测试日的表现，并提供了有关评估过程的见解。最后，我们包括案例研究，突出我们的多代理系统在表现特别强劲的时候的实例。我们发布了代码以促进对此主题的进一步研究。<sup>2</sup>

<sup>1</sup> 比赛网站可以在此找到：<https://liverag.tii.ae/index.php>

<sup>2</sup> 可在此处获得：<https://github.com/muktac5/CIIR-LiveRAG>

## 2 使用 DataMorgana 进行数据创建

为了构建 mRAG 的训练和验证数据，我们使用 DataMorgana [3] 生成了一组 QA 对。我们定义了十个不同的问题类别，然后将其组合成五种组合（每个类别的定义见附录 A）：

- 用户专业知识：该类别通过区分系统的专家用户和新手用户来指定用户在该主题上的专业水平（参见附录 A 的图 3）。
- 问题类型：这指定了问题措辞的风格，其变化沿着不同的维度，如长度（短 vs. 长）、形式（自然 vs. 查询式）和冗长度（简明 vs. 冗长），从而产生六种不同的组合（附录 A 的图 4）。
- 答案类型：这定义了答案的措辞，沿着自然与正式和简洁与冗长的维度变化，形成四种不同的组合（附录 A 中的图 10）。
- 问题意图：这定义了问题背后的意图，包括澄清、意见、比较、是/否和假设性问题等类别（附录 A 中的图 7）。
- 回答意图：这指定了回应背后的意图，分类为事实性或开放式（图 5 在附录 A 中）。
- 前提包含：这表明问题是否包含用户特定的信息，导致两种变体：有前提和无前提（附录 A 中的图 6）。
- 词汇相似性：这指的是问题与文档之间的词汇对齐：使用类似的术语、不同的术语，或引用不常见的实体（附录 A 中的图 12）。
- 方面粒度：这定义了问题是捕获主题的单个还是多个方面（附录 A 中的图 8）。
- 交互类型：这定义了问题是启动对话还是后续问题（附录 A 中的图 9）。
- 文档粒度：这说明是使用一个还是两个文档来生成问题，使用 DataMorgana 平台中的特性（附录 A 中的图 11）。

在与 DataMorgana 交互后，我们发现同时使用所有类别并不能产生高质量的输出。因此，我们在调用 DataMorgana 进行数据生成时，将其分为五个组合。所有组合都包括以下核心维度：用户专业程度、问题类型、答案类型、文档粒度、交互类型和方面粒度。每个组合中剩余的类别如下：

- 答案意图和词汇相似性。
- 前提包含
- 问题意图。
- 前提包含和问题意图。
- 词汇相似性和前提包含。

，我们使用 DataMorgana 生成 4,500 个问答对，将其中 3,500 个用于训练，1,000 个用于对我们系统的评估。数据生成过程的详细信息在附录 A 中提供。

## 3 mRAG 框架

我们的框架使用了六个执行动作的代理和一个协调代理来生成响应。mRAG 的概述如图 1 所示。本节提供了多代理系统的实现和训练细节。

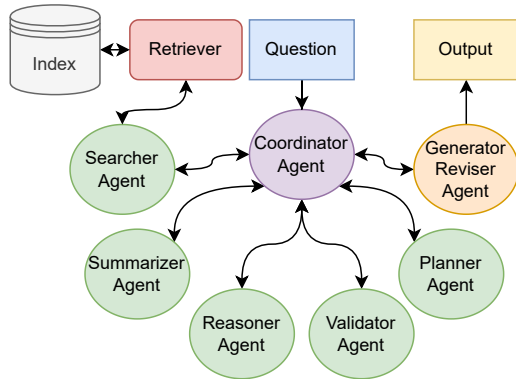


Figure 1: 多智能体 RAG 概述。

### 3.1 mRAG 中的代理

本节描述了代理的实现。

#### 3.1.1 . 协调者

这个代理作为 mRAG 的入口点。它接收一个问题和一组具有定义输入和输出格式的代理，负责根据这些代理各自的专长分配任务。在每一轮中，协调器根据当前状态和选择该代理的合理性来选择一个适当的代理，格式化并传递必要的输入，等待代理完成任务并以预期格式返回输出。接收到输出后，协调器通过将新输出附加到对话历史中来更新其内部状态，并更新响应（如果生成了一个）或支持文档集（如果检索到了新信息）。这一过程反复进行。一旦计算预算耗尽或协调器确定不再需要进一步操作且已经生成高质量的响应，它就终止该过程并返回最终响应以及支持文档。这个代理在每一步中使用具有 7B 参数的 Qwen 2.5 的指令 [12]，提示如附录 D.1 中的图 15 所示。详细实现见附录 D.1 中的算法 1。

#### 3.1.2 . 搜索者

为了访问语料库并收集回答问题所需的信息，协调者可以通过提供问题、迄今为止收集的信息以及指导搜索的建议方面，调用搜索代理。搜索代理首先生成一个搜索查询，使用具有 1B 参数的稀疏 Lion 检索模型执行该查询（详细的实现和语料库处理在附录 C 中描述）[20] 以检索到两个文档。接下来，搜索代理评估每个检索到的文档的相关性，提供理由并标记相关的文档。在此阶段，代理有三个主要选项：(1) 继续使用相同的查询进行搜索以检索下两个文档，(2) 修改搜索查询并解释新查询的理由，或 (3) 终止搜索，解释原因，并返回到目前为止找到的相关文档。该过程将一直持续到达到最大检索预算或代理决定已经收集到足够的信息为止。该设计允许搜索代理动态确定每个查询收集的适当信息量。代理在每个步骤中使用具有 7B 参数的 Instruct Qwen 2.5 模型 [12] 和附录 D.1 中图 16 所示的提示。该代理的详细实现见算法 2。

#### 3.1.3 . 规划器

该代理负责生成一系列步骤，以根据给定问题和目前收集的信息产生问题的回答。虽然协调代理可以在任何阶段调用该代理，但建议在回答生成过程的开始阶段调用。用于该代理的提示在附件 D.1 的图 17 中展示。这个代理使用具有 7B 参数的指令 Qwen 2.5 [12]。

#### 3.1.4 . 总结器

随着代理之间的对话变得越来越长，对于协调者而言，跟踪所有相关细节变得越来越具有挑战性。为了解决这一问题，

协调者可以调用该代理并提供选定的信息，以总结对话或迄今为止检索和收集的内容，使用附录 D.1 中图 18 所示的提示。这名代理使用具有 7B 参数的 Qwen 2.5 指令 [12]。

#### 3.1.5 . 推理机

当需要对检索到的信息、采取的行动或过程的任何其他方面进行逐步推理或分析时，可以通过提供问题、相关信息和需要推理的具体方面来调用该代理。该代理使用附录 D.1 中图 19 所示的提示。该代理使用具有 7B 参数的 instruct Qwen 2.5 [12]。

#### 3.1.6 . 验证器

有时，问题可能指定必须满足的某些标准。当生成响应后，协调者需要确保所有标准都得到满足时，可以调用此代理。协调者向该代理提供问题、检索到的信息和响应，随后代理从问题中提取标准，并验证它们是否在响应中得到满足，并为其每个决策提供理由。该过程使用附录 D.1 中图 20 所示的提示，采用具有 7B 参数的 instruct Qwen 2.5 [12] 进行。

#### 3.1.7 . 生成器/修订器

为了生成一个应答，协调者通过提供问题、在过程中收集的支持信息、回应计划以及一组需要包含的关键方面来调用此代理。然后，代理生成一个包含这些元素的应答。此外，如果协调者确定应答需要修改——无论是由于新收集的信息还是未满足的标准——都可以再次调用此代理，提供大纲说明缺陷及如何解决这些问题。此代理使用列在附录 D.1 图 21 中的提示。由于竞争限制，我们为此代理使用了参数为 10B 的 Falcon 3 模型的指令调优版本 [19]。

## 3.2 通过自我训练进行优化

训练多智能体系统从端到端进行挑战，因为计算效率低下且跨智能体传播梯度困难 [4, 5]。为简化训练过程，我们做出一个关键假设：智能体独立操作，仅基于其提供的输入进行功能运作。在该假设下，智能体采取的行动轨迹的概率，记为  $\tau = a_1 a_2 \dots a_n$ ，从完整的联合分布

$$p(a_1 \dots a_n | x) = p(a_1 | x) p(a_2 | a_1, x) \dots p(a_n | a_{n-1}, \dots, a_1, x)$$

简化为以下分解形式：假设在给定输入  $x$  的条件下，智能体行动条件独立。通过这种简化，我们可以使用自训练 [16] 从端到端优化系统。首先，通过应用高采样温度，我们为训练集中每个输入采样  $T = 8$  个多样化轨迹。然后，将奖励模型 RM 应用于每个轨迹的最终响应进行评分。我们仅保留每个输入中奖励评分最高的轨迹（在出现分数相同时允许最多三个轨迹，以避免在简单案例上过拟合）。这些选择的轨迹用于训练智能体重现最佳的动作序列。按照 Singh et al. [16]，通过将表现最佳轨迹的奖励  $r(\tau, x)$  设置为 1（通过将阈值分数设置为与观察到的最高奖励匹配）并将其他设置为零来规范奖励。因此，训练目标是最大化：其中  $A$  是可训练代理执行的动作集（即，除生成器/修订器外，由于竞争约束而固定的所有代理），而  $D$  是应用奖励模型后所有选择的轨迹集。这个目标相当于对代理在其自己最佳表现的输出上进行的有监督微调 [18]，以鼓励每个代理复制在最高奖励（即，最成功）轨迹中观察到的行为，促进与有效序列的一致性。训练的细节和参数在附录 D.2 中提供。

#### 3.2.1 . 奖励模型

竞赛没有提供公开可用的评分函数。然而，基于提供的指南，我们定义并使用了两个不同的奖励信号（更多实现细节在附录 D.3 中说明）：

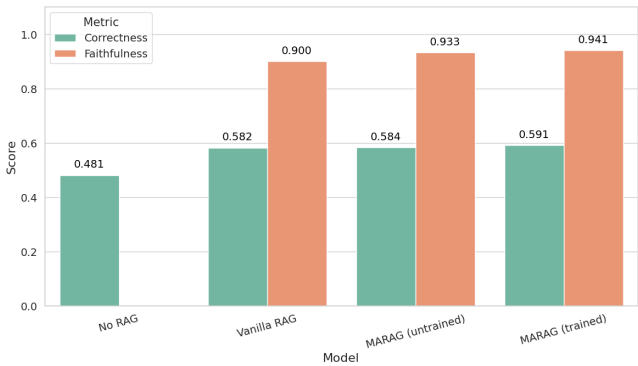


Figure 2: 使用第 3.2 节和附录 D.3 中引入的奖励模型对 mRAG 和基线进行评估。

- 正确性：我们采用了 Pradeep et al. [11] 提出的基于召回的细节奖励。在这种方法中，我们首先使用附录 D.3 中的图 22 中的提示，从真实响应中提取应该出现在输出中的原子方面。然后，使用附录 D.3 中的图 23 中的提示来评估每个提取的方面与生成响应的对齐度，分数在-1 到 2 之间。在这之后，这些分数被归一化到 [0, 1] 的范围。最终的正确性奖励是所有细节方面的平均归一化得分。具体实现详见附录 D.3 中的算法 3。
- 忠实性：这个奖励模型评估生成的应答相对于检索到的信息的忠实性。根据 Es et al. [2]，我们首先使用附录 D.3 中图 24 中的提示提取生成应答中的原子方面。然后，根据附录 D.3 中图 25 的提示，在-1 到 1 的范围内为每个方面如何被检索到的文档支持进行评分，结果随后被标准化到 [0, 1] 范围内。最终的忠实性分数是所有提取方面的标准化分数的平均值。具体实现详见附录 D.3 中算法 4。

为了计算最终奖励，我们运行每个奖励模型五次，并取每次的平均分。我们观察到 mRAG 在正确性奖励上表现最差。为了强调在这方面的改进，我们将正确性奖励赋予权重 4，忠实性奖励赋予权重 1，并计算加权平均以获得最终奖励。我们使用参数为 14B 的指令 Qwen 2.5 [12] 作为所有奖励函数的大规模语言模型。

4 实验

本节展示了我们的研究结果。实验设置在附录 D.4 中描述。为了进行比较，我们考虑了两个基线模型：一个没有检索增强的标准语言模型（vanilla LLM）和一个遵循先检索后阅读范式的检索增强生成模型（vanilla RAG）。基线系统的详细实现见附录 B。

4.0.1 . DataMorgana 所创建的测试集上的结果

我们将 mRAG 与两个基线方法进行比较：一种不带检索增强（RAG）的普通大型语言模型和一种采用检索后阅读范式的普通 RAG 系统。在来自 DataMorgana 的测试集上的评估结果如图 2 所示。研究表明，当使用第 3.2 节中描述的方法进行优化时，mRAG 在正确性和忠实性方面都优于两个基线方法。值得注意的是，即使不进行训练，mRAG 也在正确性方面可与普通 RAG 比肩，同时显示出更高的忠实性。在所有配置中，基于 RAG 的方法——mRAG 和普通 RAG——始终优于非 RAG 的基线方法。基于这些结果，mRAG 在从 DataMorgana 构建的数据集上展示了最佳的整体表现。

4.0.2 . 竞赛测试集的结果

Table 1: LiveRAG 竞赛中前 20 名参赛队伍的结果。竞赛定义的评估指标为正确性分配在-1 到 2 之间的分数，为忠实度分配在-1 到 1 之间的分数。最终排名是通过根据正确性分数对队伍进行排序来确定的。

Rank	Team	Correctness	Faithfulness
1	Magikarp	1.231	0.656
2	UDInfo	1.200	0.623
3	RMIT-ADMS	1.199	0.477
4	RAGtifier	1.134	0.552
5	HLTCOE	1.070	0.340
6	Ragmatazz	1.011	0.519
7	mRAG	0.996	0.418
8	RUC_DeepSearch	0.969	0.387
9	Ped100X	0.928	0.043
10	PRMAS-DRCA	0.922	0.410
11	Emorag	0.890	0.556
12	Graph-Enhanced RAG	0.875	0.529
13	Hybrid Search with Graph	0.875	0.315
14	Multi-Agent Adaptive RAG	0.836	0.200
15	Starlight	0.818	0.433
16	BagBag	0.694	-0.911
17	UniClustRAG	0.685	0.460
18	METURAG	0.673	0.325
19	NoobRAG	0.655	0.154
20	DeepRAG	0.566	0.097

在官方测试日进行的 LiveRAG 比赛中，mRAG 和其他前 20 个参赛系统在测试集上的结果如表 1 所示。表 1 中报告的正确性和忠实性指标的具体实施细节没有公开。然而，正确性分数范围是-1 到 2，忠实性分数范围是-1 到 1，这是由比赛组织者定义的。我们报告了竞赛评估过程中提供的原始、未归一化的分数。根据这些基于正确性指标排名的结果，mRAG 在所有参赛队伍中排名第 7 位。

4.0.3 . 基于提取的回忆导向正确性评估的不稳定性

在我们的一个实验中，我们发现仅仅提示 LLM 生成较长的回复——没有任何额外培训——就将基于信息单元的召回奖励从 0.528 提高到 0.584。这突出显示了当前评估方法中的一个关键限制：随着回复变得更长，它们更有可能包含更多的信息单元，从而夸大面向召回的奖励。然而，这以牺牲简洁和清晰为代价，导致对用户而言重复且可能不太有帮助的输出。这表明召回专注的指标可能鼓励冗长而不是精准。为了解决这一问题，未来的评估策略应该通过采用衡量相关性和简洁性来平衡召回和精准，以更好地与用户对清晰和信息丰富的回复的期望相一致。

5 案例研究

为了展示 mRAG 的有效性，我们提供了两个案例研究，这些研究展示了系统在响应用户查询时的决策轨迹和代理间的交互。这些案例研究的详细描述在附录 E 中给出。我们检查了系统在训练后对查询的响应中表现出的两个显著行为：“氢蒸汽重整的安全性问题”和“约翰·鲍尔如何影响霍伊莱克的高尔夫历史，以及该球场在界外问题上带来的策略挑战是什么？”这两个显著行为如下：



- 拆解问题并收集关于每个方面的信息：在这两种情况下，如附录 E 中的表格 2 和表格 3 所示，系统将每个问题分解为多个方面，这些方面必须被处理以形成一个全面的回应。协调员在每种情况下都两次调用搜索代理，以检索与查询两个不同方面对应的信息。检索到的信息然后被传递给负责响应生成、推理和验证的其他代理。这些互动表明，协调员已经有效地学习如何协调其他代理的贡献——尤其是搜索代理，它在支持信息获取方面发挥关键作用。
- 在检索失败后更改搜索查询：在附录 E 的表格 2 和表格 3 中的两个例子中，搜索代理展示了其对检索失败的适应性行为。当初始查询未能产生足够或相关的结果时，搜索者并不立即重新制定查询。相反，它重复使用相同的查询进行多达五次的检索尝试，旨在从较低排名的文档中提取有价值的信息——考虑到检索器可能的缺陷。仅在重复尝试之后，代理才会修改查询以探索替代的表达方式。这一行为表明搜索者已学会一种稳健的策略，用以在存在检索噪声或缺陷的情况下平衡持久性和查询重构。

更详细的案例研究内容在附录 E 中提供，该附录突出了系统在训练后表现出的几个显著的新兴行为。

## 6 结论

本文介绍了 mRAG，这是一个为 RAG 设计的多智能体框架，并提供了一种优化智能体间通信的训练方法。我们使用 DataMorgana 生成的数据训练了 mRAG，并参与了 SIGIR 2025 LiveRAG 竞赛。实验结果表明，mRAG 始终优于标准基础 RAG 模型。此外，在比赛中，mRAG 基于自动评估获得了第七名，突出了其在实际环境中的有效性。

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## A 使用 DataMorgana 创建数据的详细信息

本节提供了所有分类模式及其相应概率分布的逐字定义，用于控制与 DATA MORGANA 的生成。下列图表展示了用于通过 DATA MORGANA 结构化提示性问题生成的各个类别模式：

- 用户专业知识：每个子类别的定义及其在通过 DataMorgana 生成数据时的概率如图 3 所示。
- 问题类型：每个子类的定义及其通过 DataMorgana 生成数据的概率显示在图 4 中。
- 答案类型：每个子类别的定义及其使用 DataMorgana 生成数据的概率如图 10 所示。
- 问题意图：每个子类别的定义及其通过 DataMorgana 生成数据的概率如图 7 所示。
- 答案意图：每个子类别的定义及其生成具有 DataMorgana 数据的概率如图 5 所示。
- 前提包含：每个子类别的定义及其与 DataMorgana 生成数据的概率如图 6 所示。
- 词汇相似度：每个子类别的定义及其通过 DataMorgana 生成数据的概率显示在图 12 中。

```

user_expertise = {
  "categorization_name": "user-expertise",
  "categories": [
    {
      "name": "expert",
      "description": "an expert on the subject discussed in the documents, therefore he asks complex questions.",
      "probability": 0.50
    },
    {
      "name": "novice",
      "description": "a person with very basic knowledge on the topic discussed in the topic. Therefore, he asks very simple questions.",
      "probability": 0.50
    }
  ]
}

```

Figure 3: 用户专业知识分类方案和概率。

- 方面粒度：每个子类别的定义及其使用 DataMorgana 生成数据的概率如图 8 所示。
- 交互类型：每个子类别的定义及其使用 DataMorgana 生成数据的概率如图 9 所示。
- 文档粒度：每个子类别的定义及其使用 DataMorgana 生成数据的概率如图 11 所示。

如前所述，我们观察到同时对所有类别进行条件处理通常会导致不连贯或质量下降的输出。为了缓解这个问题，我们设计了以下五种兼容的类别组合以进行受控生成：

- (1) 用户专长, 问题类型, 答案类型, 文档粒度, 交互类型, 方面粒度, 答案意图, 和词汇相似性。
- (2) 用户专长, 问题类型, 答案类型, 文档粒度, 交互类型, 方面粒度, 和前提包含。
- (3) 用户专长, 问题类型, 答案类型, 文档粒度, 交互类型, 方面粒度, 和问题意图。
- (4) 用户专长, 问题类型, 答案类型, 文档粒度, 交互类型, 方面粒度, 前提包含, 和问题意图。
- (5) 用户专长, 问题类型, 答案类型, 文档粒度, 交互类型, 方面粒度, 词汇相似性, 和前提包含。

## B 基线实现细节

作为本文的基线，我们使用了两个不同的模型：

- 无检索基线：我们使用与 mRAG 中相同的生成器，即经过指令微调的具有 10B 参数的 Falcon 模型<sup>3</sup> [19]，但没有任何检索。模型直接使用图 13 中显示的提示来回答问题。
- 原始 RAG：再次使用经过指令调优的 Falcon 10B 模型 [19]，这个基线方法整合了检索功能。文档首先使用与 mRAG 相同的检索模型和配置，使用问题本身作为查询进行检索。检索到的文档随后与问题一起传递给 LLM，以生成使用图 14 中所示提示的响应。

，其中两个基线都使用核采样 [6]，生成的温度为 0.1。在检索时，我们始终检索两个文档，类似于 mRAG。

## C 检索器实现细节

为了实现高效的索引和文档级检索，我们通过将长文档分割成较小的重叠块来预处理原始的 FineWeb 语料库。每个块限制为 512 个标记，并有 80 个标记的重叠以保持局部连贯性。这

<sup>3</sup>可在：<https://huggingface.co/tiiuae/Falcon3-10B-Instruct>

```

question_phrasing_categorization = {
  "categorization_name": "question-phrasing-type",
  "categories": [
    {
      "name": "concise and natural",
      "description": "You should generate a concise, direct, and naturally phrased question consisting of a few words.",
      "probability": 0.35
    },
    {
      "name": "verbose and natural",
      "description": "You should generate a relatively long question consisting of more than 9 words, written in fluent, natural-sounding language.",
      "probability": 0.35
    },
    {
      "name": "short search query",
      "description": "You should generate a short query consists of less than 7 words phrased as a typed web query for search engines only keywords, without punctuation and without a natural-sounding structure.",
      "probability": 0.1
    },
    {
      "name": "long search query",
      "description": "You should generate a long query consists of more than 7 words phrased as a typed web query for search engines only keywords, without punctuation and without a natural-sounding structure.",
      "probability": 0.1
    },
    {
      "name": "concise and fancy",
      "description": "You should generate a short, well-structured question expressed in a stylistically rich or sophisticated manner.",
      "probability": 0.05
    },
    {
      "name": "verbose and fancy",
      "description": "You should generate a long and elaborate question phrased with refined, elevated, or formal language, often using complex sentence structures.",
      "probability": 0.05
    }
  ]
}

```

Figure 4: 问题类型分类方案和概率。

种分块策略将数据集从约 1400 万篇原始文档扩展到近 2900 万条索引单元。为了在推理和索引过程中的一致性，我们为这些块分配了连续的数字 ID（例如，1, 2, 3 等），并存储了这些 ID 与原始 FineWeb 文档标识符之间的映射以便追溯。

对于我们的检索设置，我们使用了来自 Hugging Face 的最先进的稀疏检索模型 Lion。这个拥有 10 亿参数的模型被用来索引文档并检索结果，遵循我们实验室之前的方法。该方法在 MS MARCO 数据集上达到了最先进的性能，并在 FineWeb 数据集上展示了相当的结果。

**C.0.1 索引：**在索引过程中，我们将每个文档块编码为一个维度为 128k 的稀疏向量（对应模型的词汇表大小），并仅保留

```
factuality_categorisation = {
  "categorization_name": "factuality",
  "categories": [
    {
      "name": "factoid",
      "description": "A question seeking a specific, concise piece
of information or a short fact about a particular subject, such as a
name, date, or number.",
      "probability": 0.50
    },
    {
      "name": "open-ended",
      "description": ("question inviting detailed or exploratory
responses, encouraging discussion or elaboration."
      "e.g., 'what caused the French revolution?"),
      "probability": 0.50
    }
  ]
}
```

Figure 5: 答案意图分类方案和概率。

```
premise_categorization = {
  "categorization_name": "premise-categorization",
  "categories": [
    {
      "name": "without premise",
      "description": "a question that does not contain any premise
or any information about the user.",
      "probability": 0.70
    },
    {
      "name": "with premise",
      "description": "a question starting with a very short premise,
where the users reveal their needs or some information about
themselves.",
      "probability": 0.30
    }
  ]
}
```

Figure 6: 前提包含分类方案和概率。

非零的令牌权重对。这些表示被存储在磁盘上的倒排索引中。生成的索引大约占用 571 GB 的存储空间。

在推理阶段，传入的查询被标记化并使用相同的模型和投影头编码为稀疏查询向量。检索是通过查询向量和倒排索引之间的 CPU 端稀疏点积计算进行的，并使用 Numba 加速<sup>4</sup>实现多线程执行。我们默认使用  $k$  检索策略，值为  $k = 2$ ，并应用 0.0 的阈值来筛选低分文档。整个检索栈通过 FastAPI<sup>5</sup> 服务呈现，支持单个和批量查询。

<sup>4</sup>可在: <https://github.com/numba/numba>

<sup>5</sup>可在: <https://github.com/fastapi>

```
question_intent_categorization = {
  "categorization_name": "question-intent-type",
  "categories": [
    {
      "name": "clarification",
      "description": "A question seeking further explanation or details about a
specific concept, term, or methodology",
      "probability": 0.20,
    },
    {
      "name": "opinion",
      "description": "A question asking for a subjective viewpoint.",
      "probability": 0.20,
    },
    {
      "name": "comparison",
      "description": "A question that compares the information in the document
to other studies, perspectives, or contexts.",
      "probability": 0.20,
    },
    {
      "name": "yes_no_question",
      "description": "A question expecting a yes or no answer",
      "probability": 0.20,
    },
    {
      "name": "hypothetical",
      "description": "A question imagining a what-if scenario, asking about
potential futures, counterfactual histories, or theoretical cases. Use this category
only when the document includes reflective or interpretive content such as
commentary on history, society, science, technology, philosophy, or human
behavior. Ex: What if climate data from the 1800s had been digitized?",
      "probability": 0.20,
    }
  ]
}
```

Figure 7: 问题意图分类方案和概率。

```
question_aspect_categorisation = {
  "categorization_name": "aspect-type",
  "categories": [
    {
      "name": "single-aspect",
      "description": "A question focused on one specific aspect or dimension of
a concept or entity (e.g., What are the benefits of using AI in diagnostics?).",
      "probability": 0.50
    },
    {
      "name": "multi-aspect",
      "description": "A question about two different aspects of the same
entity/concept (e.g., What are the advantages of AI-powered diagnostics, and
what are the associated risks of bias in medical decision-making?).",
      "probability": 0.50
    }
  ]
}
```

Figure 8: 方面粒度分类架构和概率。

## D mRAG 的实现细节

### D.1 提示和算法

本节概述了共同构成 mRAG 的代理实现细节。每个代理都被赋予特定的角色，并相应地通过 Qwen 2.5 模型（具有 7B 参

```
question_turn_categorisation = {
  "categorization_name": "question-turn",
  "categories": [
    {
      "name": "single-turn",
      "description": "The initial question of a conversation, self-contained and understandable without any prior context.",
      "probability": 0.50,
    },
    {
      "name": "two-turn",
      "description": "A follow-up or compound question that either builds on previous context or combines two sub-questions on related or evolving concepts.",
      "probability": 0.50,
    }
  ]
}
```

Figure 9: 交互类型分类模式和概率。

```
answer_type = {
  "categorization_name": "answer-phrasing-type",
  "categories": [
    {
      "name": "concise and natural",
      "description": "Expects a brief, direct answer, typically a short phrase or sentence using everyday, accessible language.",
      "probability": 0.4
    },
    {
      "name": "verbose and natural",
      "description": "Expects a detailed yet conversational response, typically one or more full sentences.",
      "probability": 0.4
    },
    {
      "name": "concise and fancy",
      "description": "Expects a brief answer, typically one sentence or phrase, but expressed in an elevated, stylistically rich, or formal tone.",
      "probability": 0.1
    },
    {
      "name": "verbose and fancy",
      "description": "Expects a longer and more elaborate answer, delivered in a refined, ornate, or sophisticated style, often using complex sentence structures and rich vocabulary.",
      "probability": 0.1
    }
  ]
}
```

Figure 10: 答案类型分类方案和概率。

```
multi_doc_categorization = {
  "categorization_name": "number-of-documents",
  "categories": [
    {
      "name": "multi-doc",
      "description": (
        "The information required to answer the question needs to come from two documents, specifically, "
        "the first document must provide information about the first entity/concept, while the second must "
        "provide information about the second entity/concept."
      ),
      "probability": 0.5,
      "is_multi_doc": True
    },
    {
      "name": "single-doc",
      "description": (
        "The information required to answer the question can be found in a single document, "
        "which contains all the necessary information about the entity/concept."
      ),
      "probability": 0.5,
      "is_multi_doc": False
    }
  ]
}
```

Figure 11: 文档粒度分类方案和概率。

```
document_type_categorization = {
  "categorization_name": "linguistic-variation-type",
  "categories": [
    {
      "name": "similar-to-document",
      "description": "phrased using the same terminology and phrases appearing in the document (e.g., for the document 'The Amazon River has an average discharge of about 215,000–230,000 m³/s', 'what is the average discharge of the Amazon river')",
      "probability": 0.3
    },
    {
      "name": "distant-from-document",
      "description": "phrased using terms completely different from the ones appearing in the document (e.g., for a document 'The Amazon River has an average discharge of about 215,000–230,000 m³/s', 'How much water run through the Amazon?')",
      "probability": 0.4
    },
    {
      "name": "unpopular-entities",
      "description": "a question focusing on rare, less-documented, or emerging entities not widely mentioned in the fineweb corpora.",
      "probability": 0.3
    }
  ]
}
```

Figure 12: 词汇相似性分类模式和概率。

数)<sup>6</sup> [12] 进行提示，或者在生成和修订响应的情况下，通过 Falcon 3 模型（具有 10B 参数）[19] 进行提示。协调器代理的提示和逻辑详见图 15 和算法 1，它通过根据上下文和代理专长将任务分配给其他代理来管理整体工作流程。它迭代地处理

<sup>6</sup>可用于：<https://huggingface.co/Qwen/Qwen2.5-7B-Instruct>

代理输出，更新对话历史并决定何时以最终答案终止。计划者（图 17）生成推理步骤的高级序列，而搜索者（图 16，算法 2）使用 Lion 检索模型 [20] 检索相关文档并动态调整其搜索策略。为了支持扩展性并保持连贯性，摘要代理（图 18）压缩了累积的内容，帮助协调器维护上下文。当需要深入分析推



**Non-RAG Baseline Prompt**

You are a helpful assistant. You will be given a question and you need to answer it.

# question: {QUERY}

Figure 13: 用于非 RAG 基线的提示。

**RAG Baseline Prompt**

You are a helpful assistant. You will be given a question and a set of supporting documents. You can use the documents to answer the question accurately. You should generate a response that is relevant to the question and supported by the documents.

# input:

- "question": the question you need to answer
- "supporting documents": a list of documents that can be used to answer the question.

# output: You should generate a valid JSON object enclosed in the ```json``` block. The JSON object should contain the following fields:

- "response": the answer to the question. The answer should be relevant to the question and supported by the documents.

# question: {QUERY}

# documents:

Document 1: [DOC\_1]

...

Document K: [DOC\_K]

Figure 14: 用于 RAG 基线的提示，该基线使用检索和阅读范式。

理时，会调用推理者（图 19）处理特定方面的信息。验证者（图 20）通过分析问题和输出之间的一致性，确保生成的响应符合所有特定问题标准。最后，由 Falcon 3 [19] 支持的生成/修订代理（图 21）生产并在需要时完善响应，以确保完整性和连贯性。这些代理一起在一个紧密协调的循环中运作，其各自的行为在相应的图和算法中被形式化。

## D.2 训练设置

为了训练模型，我们首先为训练集中的每个输入采样  $T = 8$  种多样的轨迹。对于所有的代理（除了响应生成器/修订器），我们使用温度为 0.7 的核采样来鼓励探索并促进轨迹多样性。由于竞赛限制，响应生成器/修订器代理使用核采样 [6] 和温度为 0.1 进行采样，因为它不可训练。较低的温度减少了随机性，导致更确定性的输出，这使得可训练的代理能够更好地适应生成器/修订器的固定行为。

为了训练代理，我们使用单个共享的 LoRA [7] 适配器来进行所有可训练代理，而不是为每个代理单独使用适配器。这个适配器的秩为  $r = 16$ ，用于优化指令调教的 Qwen 2.5 拥有 7B

参数的 LLM [12] 中的所有线性层。我们使用 Unsloth<sup>7</sup> 进行高效和快速训练。采取 Adam 优化器 [10]，学习率为  $10^{-4}$ 。应用最大范数为 1 的梯度裁剪。训练过程最多进行 5,000 步，包括一个线性学习率调度的 50 步预热阶段。模型在每 500 步时对测试集进行评估，选择表现最佳的检查点。最大输入和输出长度的总和和设置为 16,000 个 tokens。所有实验的批量大小为 128。所有训练在单个 NVIDIA A100 GPU 上进行。

## D.3 奖励模型

该竞赛没有提供官方评分函数，因此我们根据给定的评估指南定义并实现了两个互补的奖励信号——正确性和忠实性。正确性通过 Pradeep et al. [11] 中的以回忆为导向的基于要素的奖励进行评估，其中从地面真相中提取原子方面（图 22），然后使用评分提示对生成的响应进行对齐（图 23）。这些分数被归一化到  $[0, 1]$ ，并平均生成最终的正确性奖励，完整实施见算法 3。忠实性遵循 Es et al. [2] 的方法，涉及原子声明的提取（图 24）并验证其针对检索文档的支持（图 25），最终分数计算为平均归一化分数（算法 4）。为了减少方差并确保稳定的奖励建模和估计，每个奖励模型以 0.5 的温度使用核心采样 [6] 执行五次，并平均分数。根据经验，我们观察到 mRAG 在正确性维度上的表现较差。为了优先改善这一领域，我们在最终奖励计算中应用了加权方案：正确性赋予权重 4，而忠实性权重为 1。然后通过两者归一化分数的加权平均计算最终奖励，在优化过程中有效地强调正确性以更好地进行改善。我们使用经过指令微调的 Qwen 2.5，其具有 140 亿参数<sup>8</sup> [12]，作为所有奖励函数的主干 LLM。

## D.4 推理设置

为了使用 LLM 进行推理，我们利用 vLLM 库<sup>9</sup> 提供语言模型服务。生成时使用 0.1 的温度和核采样。每个代理的最大输入输出令牌长度总和和设定为 32,000 个令牌。协调代理可以最多调用其他代理 30 次。搜索代理可以重复使用相同的查询最多 5 次，没有额外的预算限制。检索模型设置的详细信息在附录 C 中提供。

## E 案例研究

所提出的多代理系统表现出显著且令人印象深刻的行为，特别是在协调员和搜索员代理的决策过程中，这些代理肩负着比其他代理更复杂的责任。为了更深入地探索这些行为，我们研究两个具有代表性的案例研究。

### E.0.1 多方面问题

在输入问题涉及多个维度并需要收集跨越不同方面的信息的情况下，系统必须有效地检索和整合来自这些不同维度的信息，以生成连贯且高质量的回应。一个此类查询的例子是“氢气蒸汽重整的安全问题”，这要求系统识别和综合该过程中多个与安全相关的方面的信息。为响应该问题，代理之间的完整互动如表 2 所示。

为了解决这个问题，作为系统入口的协调者首先调用计划代理，将问题分解为一系列可操作的步骤。计划者将任务分解为识别氢气蒸汽重整的关键组件、收集每个组件的信息、搜索相关的安全隐患，并将收集的信息综合成一个连贯的回应。随后，协调者指导搜索代理，提供建议以引导检索与指定方面相关的信息。搜索者然后执行针对性的查询并返回相关信息。使

<sup>7</sup>可用于: <https://github.com/unslothai/unsloth>

<sup>8</sup>可获得于: <https://huggingface.co/Qwen/Qwen2.5-72B-Instruct>

<sup>9</sup>可在此处获取: <https://github.com/vllm-project/vllm>



**Coordinator Agent Prompt**

You are a highly capable agent, and your goal is to generate a response to the given question. This is a multi-turn task and you don't have to do it in a single turn. You have access to a set of capable agents, each with a specific skill, and you can choose the most suitable agent for each turn to help you in generating the response. In each turn, you should select the most suitable agent from a provided list of agents to help you generate the response. The agents can help you in different aspects such as validating the response, searching for information, analyzing the information, and summarizing the information. Your goal is to generate a response that is informative and relevant to the question. You can use the agents to help you in different aspects of generating the response. You can also use the agents multiple times to generate the response. You can also use the agents in any order you like. To choose an agent, you need to provide the a valid json object in ```json``` block that contains the following fields:

- "agent": the name of the agent you want to choose.
- "input": the input you want to provide to the agent. This should be a valid json object that contains the required fields for the chosen agent.
- "reason": a brief explanation of why you chose the agent for the given input.

In response, the agent will provide you with the output in the specified format for the chosen agent. The list of agents and their input and output formats are provided below:

**# Agents:**

**## validator:** This agents can help you verify if the generated response meets the criteria for the given question.

**### input:**

- "question": the question the user wants to answer.
- "information": the information the you has gathered so far and want to share with the agent. This can be a summary or highlights of the information you have gathered so far and does not need to be the full information. This can be empty if you have not gathered any information yet.
- "response": the response generated to the question.

**### output:**

- "extracted\_criteria": a list of criteria that are extracted from only the user's question (e.g., being detailed, concise, short, long, etc.), containing the following fields:
  - "criteria": the criteria extracted from the user's question.
  - "criteria\_explanation": an explanation of why extracted this criteria.
- "is\_response\_valid": a boolean value indicating whether the response is valid according to the extracted criteria.
- "is\_response\_valid\_feedback": feedback on whether the response is valid according to the extracted criteria and how it can be improved.
- "is\_groundedly\_supported": a boolean value indicating whether the all parts of the response is grounded with supporting information.
- "is\_groundedly\_supported\_feedback": feedback on whether the response is grounded with supporting information and how it can be improved.
- "is\_correctly\_answered": a boolean value indicating whether the response is correct.
- "is\_correctly\_answered\_feedback": feedback on whether the response is correct and how it can be improved.

**## summarizer:** This agent can help you summarize the information you have gathered so far.

**### input:**

- "question": the question the user wants to answer.
- "information": the information you have gathered so far and want to summarize. This can be empty if you have not gathered any information yet.

**### output:**

- "summary": the summary of the information that the agent has generated.

**## planner:** This agent can help you plan a strategy to generate the response to the given question. It is suggested to use this agent at the beginning of the task to plan the strategy. You can also use this agent multiple times in any time during the task to plan the strategy.

**### input:**

- "question": the question the user wants to answer.
- "information": the information you have gathered so far and want to share with the agent. This can be a summary or highlights of the information you have gathered so far and does not need to be the full information. This can be empty if you have not gathered any information yet.

**### output:**

- "plan": the plan that the agent has generated to generate the response to the given question.

**## reasoner:** This agent can help you reason about the information you have gathered so far about specific aspects of the question. You can use this agent to reason about the information you have gathered if you need help with reasoning about the information.

**### input:**

- "question": the question the user wants to answer.
- "information": the information you have gathered so far and want to reason about. This can be a summary or highlights of the information you have gathered so far and does not need to be the full information. This can be empty if you have not gathered any information yet.
- "aspect": the aspect of the question you want to reason about.

**### output:**

- "analysis": the reasoning about the information that the agent has generated.

**## answerer:** This agent can help you generate the response to the given question. You can use this agent to generate the response to the question. You can use this agent multiple times in any time during the task to generate the response.

**### input:**

- "question": the question the user wants to answer.
- "guidance": a guidance on how should the agent structure its response and what to include in this response. This should help the agent to generate a better response based on the information you have gathered so far, but it should not be the answer itself.
- "important\_information": a string that outlines the most important information that should be included in the response.

**### output:**

- "response": the response that the agent has generated to the given question.

**## reviser:** This agent can help you revise the response generated by the answerer agent. You can use this agent to revise the response generated by the answerer agent if you need help with revising the response. Note that you cannot use this agent before answerer agent.

**### input:**

- "question": the question the user wants to answer.
- "suggestion": a string that outlines the suggested revisions to the response.

**### output:**

- "response": the revised response that the agent has generated.

**## searcher:** This agent can help you search for information that can help you answer the given question. You can use this agent to search for information that can help you answer the question. You can use this agent multiple times in any time during the task to search for information.

**### input:**

- "question": the question the user wants to answer.
- "information": the information you have gathered so far and want to share with the agent. This can be a summary or highlights of the information you have gathered so far and does not need to be the full information. This can be empty if you have not gathered any information yet.
- "suggestions": a set of suggestions about what aspect to search for.

**### output:**

- "found\_information": a boolean value indicating whether the search found relevant information.
- "documents": a list of documents that the agent has found that are relevant to the search query.

**## finisher:** You can end the task by using this agent. By selecting this agent, you indicate that you have finished the task and the latest response generated by the answerer or reviser agent is the final response to the question.

**### input:**

- "finished": a boolean value indicating that you have finished the task.

**### output:** the agent will not provide any output.

**### Note:** You should only provide this input to the agent in the given format and you don't need to provide the response to the agent.

**# question:** {QUESTION}

To choose an agent, you need to provide the a valid json object in ```json``` block that contains the following fields:

- "agent": the name of the agent you want to choose.
- "input": the input you want to provide to the agent. This should be a valid json object that contains the required fields for the chosen agent.
- "reason": a brief explanation of why you chose the agent for the given input.

In response, the agent will provide you with the output in the specified format for the chosen agent. In selecting an agent, you should select the agent that you think is the most appropriate to take next. Using the same agent multiple times is allowed if you think it is necessary, but might not be useful always. In response, the agent will provide you with the necessary information to continue the conversation.

Figure 15: 在 mRAG 框架中用于协调员代理的提示。

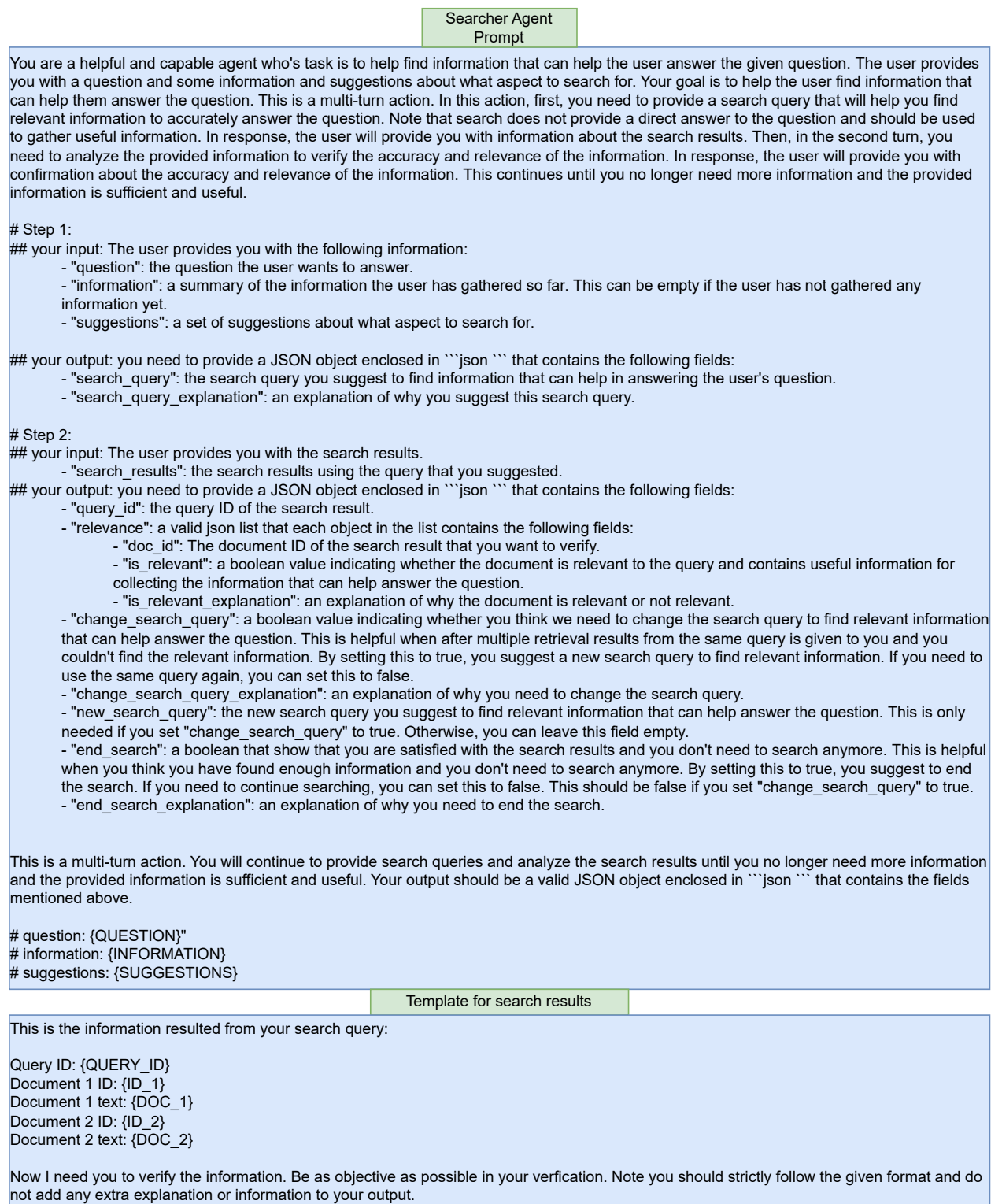


Figure 16: 用于 mRAG 框架中的 Searcher 代理的提示。

**Algorithm 1** 在 mRAG 框架中实现协调器代理。**Input:** question  $q$ , agents list  $A$ , LLM  $\pi$ **Output:** response to the question  $r$ , supporting documents  $S$ 

```

1:  $i = 0$                                 ▶ Counter of number of steps/calls to agents
2:  $finish = False$                         ▶ Initializing variables for when to end process
3:  $agents\_outputs = []$                   ▶ Initializing variables for saving the state of agents
4:  $S = \{\}$                                 ▶ Initializing variables for collecting supporting documents
5:  $r = ""$                                 ▶ Initializing variables for final response
6: while  $i < MAX\_STEPS$  and  $finish = False$  do
7:    $agent\_name, agent\_inputs = \pi(q, agents\_outputs, S)$ 
8:   if  $agent\_name = Finish$  then
9:     Break
10:  end if
11:   $a = select\_agent(A, agent\_name)$       ▶ Select the agent from agents list
12:   $selected\_agent\_output = a(agent\_inputs)$  ▶ Call the agent with the given input parameters generated by coordinator
13:   $agents\_outputs = agents\_outputs + [selected\_agent\_output]$  ▶ Updating the state of the coordinator with the agent's output by
    appending
14:   $i = i + 1$                             ▶ Updating the step
15:  if  $agent\_name = generator$  or  $agent\_name = reviser$  then ▶ If the selected agent generates a new response i.e., generator or
    reviser
16:     $r = agents\_outputs$                 ▶ Replace the response with the new response
17:  end if
18:  if  $agent\_name = searcher$  then        ▶ If the selected agent collects supporting information i.e., searcher agent
19:     $S = S \cup agents\_outputs$             ▶ Add the new supporting information to all supporting information
20:  end if
21: end while
22: return  $r, S$                             ▶ Returning the response and supporting documents

```

**Algorithm 2** 在 mRAG 框架中实现 Searcher 代理。**Input:** question  $q$ , context information  $c$ , suggested search aspects  $a$ , retrieval model  $R$ , LLM  $\pi$ **Output:** relevant retrieved documents set  $S$ 

```

1:  $S = \{\}$                                 ▶ Initializing the relevant documents set
2:  $i = 0$                                 ▶ Counter of number of retrieval steps
3:  $end\_search = False$ 
4:  $query = \pi(q, c, a)$ 
5: while  $i < MAX\_STEPS$  and  $end\_search = False$  do
6:    $this\_step\_docs = R(query, 2)$         ▶ retrieve two docs for query. If this query is issued before, return next 2 docs for query.
7:   for  $d \in this\_step\_docs$  do            ▶ For each document in the retrieved document for the query
8:     if  $\pi(query, d) = relevant$  then    ▶ If document is relevant to the query
9:        $S = S \cup \{d\}$                 ▶ Add the document to the relevant documents set
10:    end if
11:  end for
12:   $i = i + 1$                             ▶ Updating the step
13:   $change\_query = \pi(query, this\_step\_docs, S)$  ▶ Check if we need to change the query
14:   $end\_search = \pi(query, this\_step\_docs, S)$  ▶ Check if we need to end the search process
15:  if  $change\_query = True$  then
16:     $query = \pi(query, this\_step\_docs, S)$  ▶ Updating the search query if it needs update
17:  end if
18: end while
19: return  $S$                             ▶ Returning the relevant retrieved documents

```



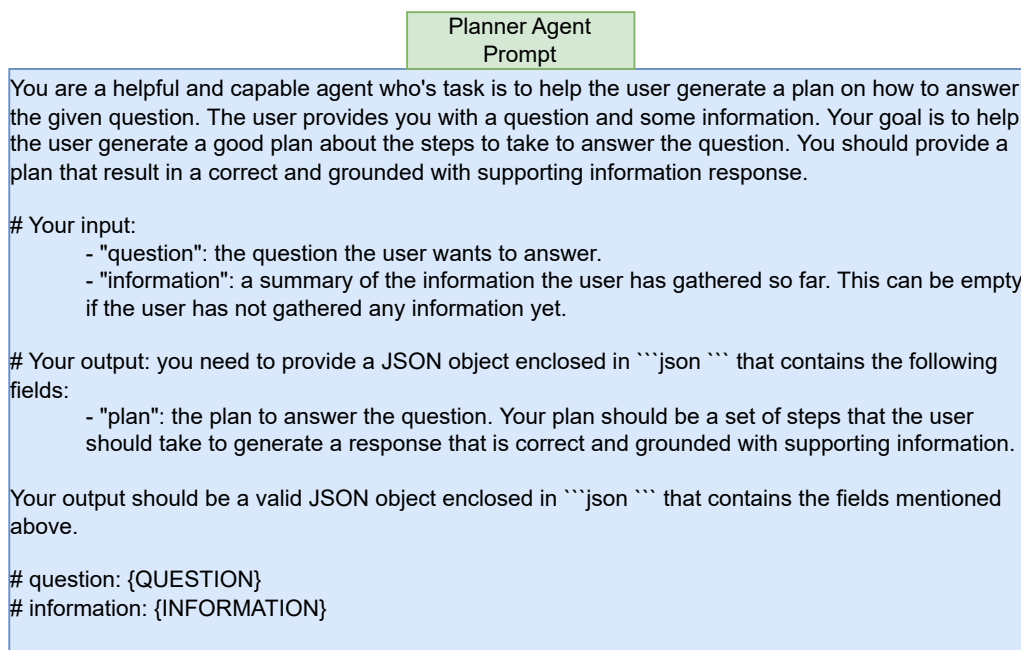


Figure 17: 用于 mRAG 框架中规划代理的提示。

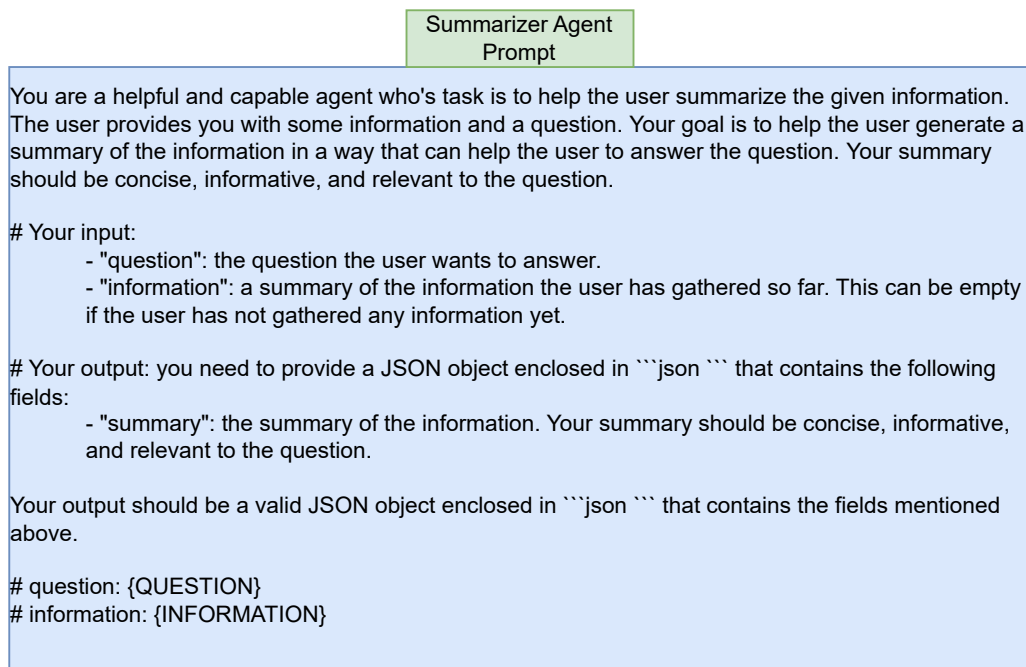


Figure 18: 在 mRAG 框架中用于总结器代理的提示。

用推理代理分析该过程的安全性之后，协调者指示搜索者收集与氢气蒸汽重整相关的现实历史安全事故的信息。搜索者使用检索模型获取相关文件，并将收集的数据返回给协调者。鉴于检索信息的量，协调者然后调用摘要代理将内容浓缩为

统一的形式。随后，协调者调用生成代理，提供聚合的证据并指示其生成一个全面的回应。生成器特意被指导包括氢气蒸汽重整所涉及的关键组件详细概述、每个组件的相关安全隐患、记录的历史事件以及目前的安全指南和法规。一旦回应生

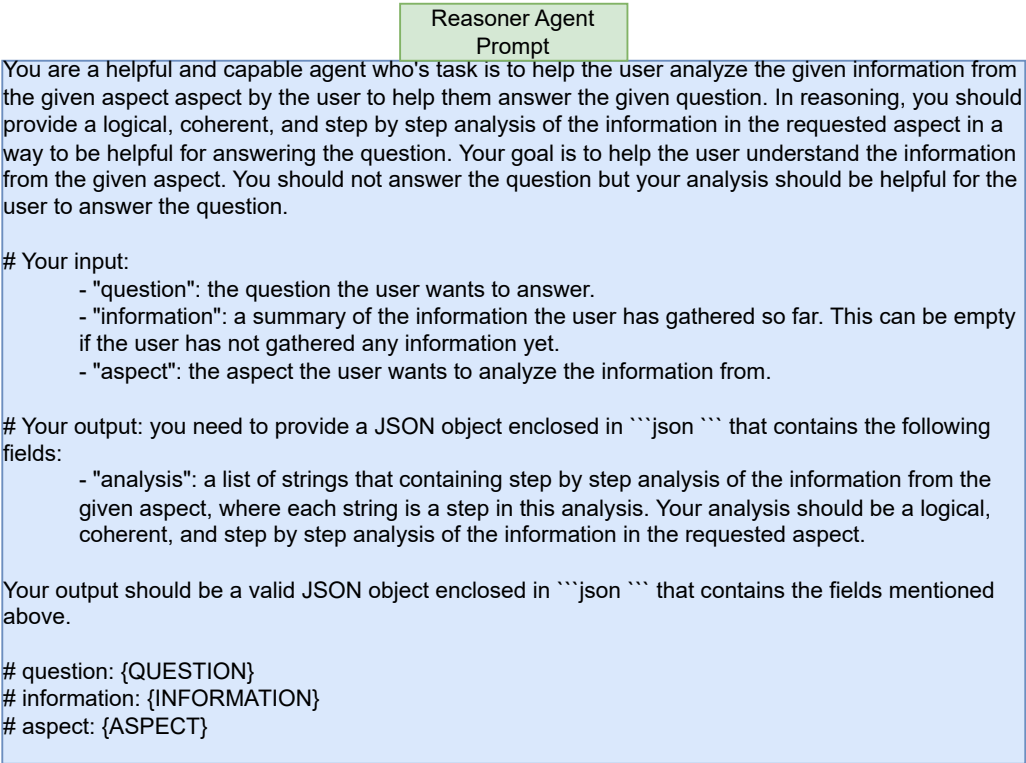


Figure 19: mRAG 框架中用于推理代理的提示。

成，协调者咨询验证代理以核实回应是否符合定义的标准。验证者强调了完整性和深度的重要性，特别因为查询的关键性质。在确认所有标准都满足后，协调者结束流程并返回回应。

回复被传递给验证代理进行评估。一旦所有标准被满足，协调者结束流程并返回最终回复。

E.0.2 . 检索更多信息以确保收集到足够的信息

除了需要整合多个方面的情况外，有些查询即使是针对单个方面，检索相关信息也会面临挑战，通常是由于检索模型的局限性所致。在这种情况下，稳健的 RAG 系统必须能够检测检索失败，并主动重新制定搜索查询，以获得更相关的内容。为了展示这种能力，我们研究系统对以下查询的响应：“约翰·鲍尔如何影响荷伊湖高尔夫历史，与界外相关的课程呈现了哪些战略挑战？”如表 3 所示。

为了解决这个问题，协调者首先调用计划代理生成一个结构化的计划。生成的计划包括以下步骤：确定约翰·鲍尔在高尔夫历史上的角色，检索他在霍伊莱克的职业生涯中的关键事件或里程碑，并通过历史记录和专家分析考察界外（OB）规则对比赛的演变和影响。在该计划的指导下，协调者随后委派搜索代理检索有关约翰·鲍尔对霍伊莱克高尔夫历史影响的信息，此任务成功完成。随后，调用推理代理分析约翰·鲍尔的贡献。在这一推理过程中，识别出需要收集有关霍伊莱克球场战略挑战的额外信息。然而，初次的检索尝试未能产生相关内容。为解决此问题，搜索者重新调整查询，专注于“霍伊莱克皇家利物浦高尔夫俱乐部的战略挑战”，从而成功检索到相关信息。然后，协调者调用生成器代理，利用收集的证据生成一份全面的回复。本案例研究中，如之前案例学习中一样，此

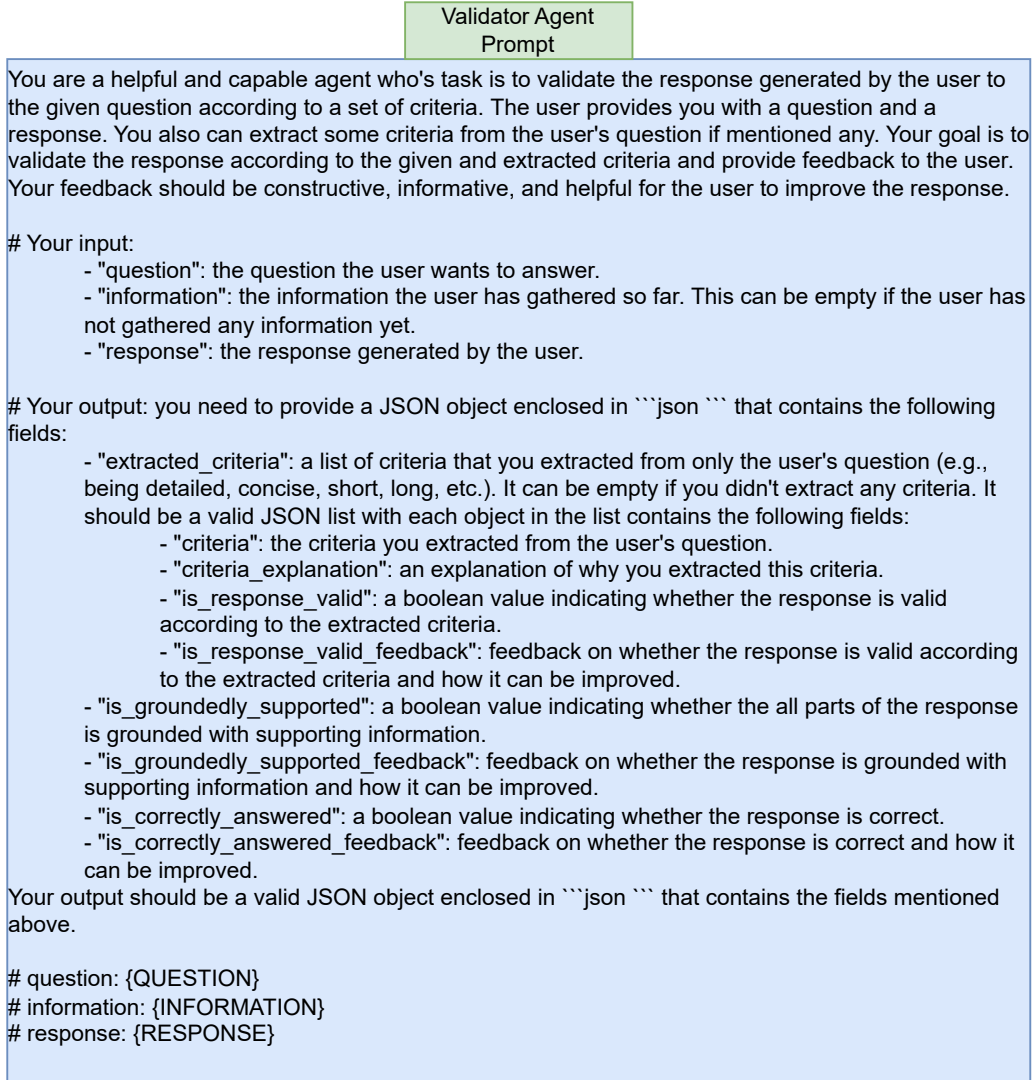


Figure 20: 在 mRAG 框架中用于验证器代理的提示。

**Algorithm 3** 正确性奖励模型的实现。**Input:** question  $q$ , generated response  $r$ , ground truth response  $gt$ , evaluator LLM  $\pi$ **Output:** correctness score  $s_f$ 

```

1:  $extracted\_aspects = \pi(q, gt)$  ▷ Extracting the atomic aspects from the ground truth output
2:  $S_f = 0$ 
3: for  $aspect \in extracted\_aspects$  do ▷ For each of the extracted aspects from the ground truth response
4:    $S_{aspect} = \frac{\pi(q, aspect, r, gt) + 1}{3}$  ▷ Score the aspect using the LLM in range of -1 and 2, then normalize it to 0 and 1
5:    $S_f = S_f + \frac{S_{aspect}}{|extracted\_aspects|}$  ▷ Adding the score of aspect to the final score
6: end for
7: return  $s_f$  ▷ Returning the correctness score for the generated response

```



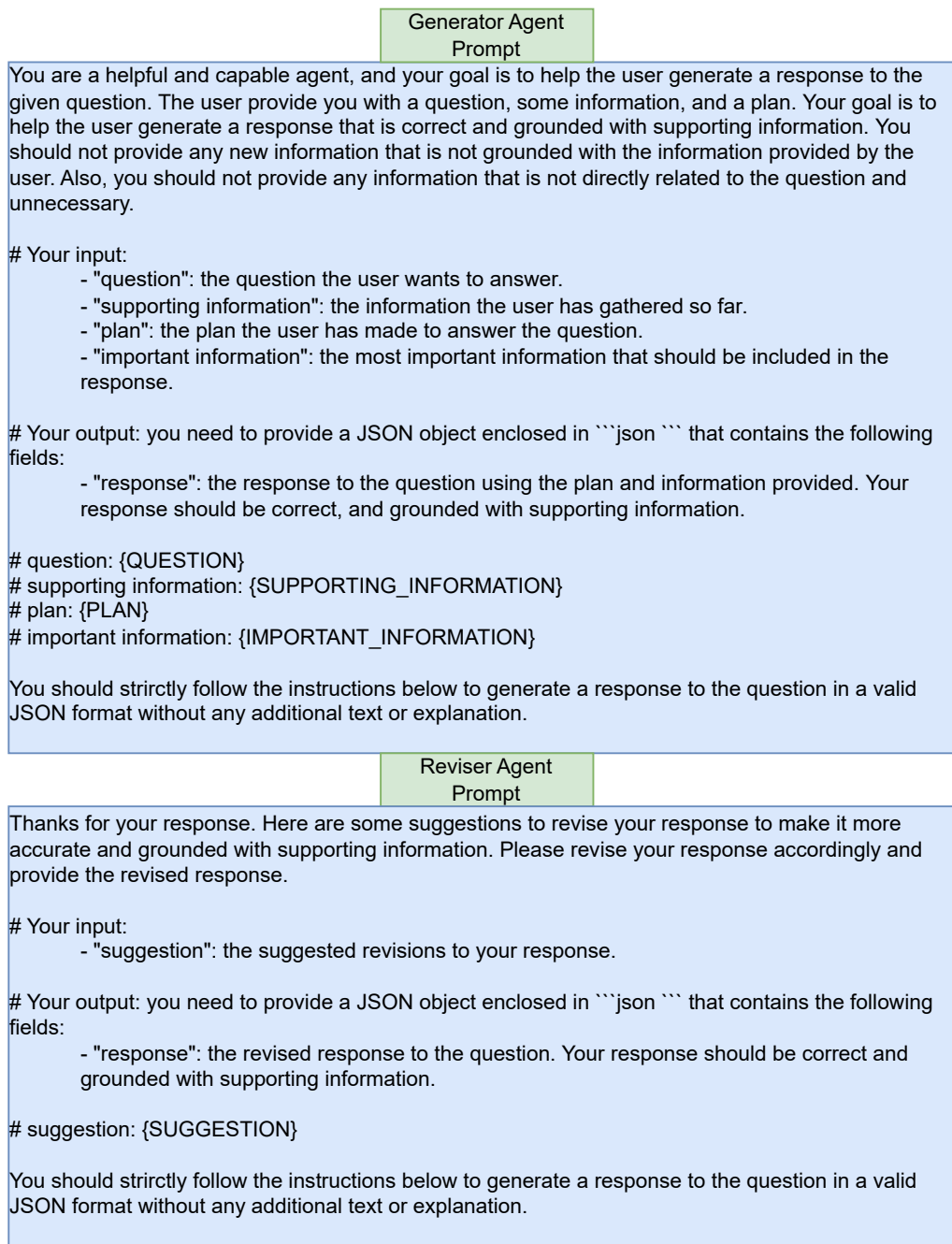


Figure 21: 在 mRAG 框架中用于生成器/修订者代理的提示。

### Extracting Aspects for Coverage Reward

You are an impartial judge who has been asked to evaluate how the generated output answers the question. Your task is to given an expected output for a given question, extract all atomic pieces of information from the expected output. These atomic pieces of information are the smallest units of information that discuss a single unique aspect of the answer to the question.

# Your input:

- "question": The question that was asked
- "expected\_output": The expected output.

# your output: you need to provide a JSON object enclosed in ```json ``` that contains the following fields:

- "expected\_output\_aspects": a list of atomic pieces of information extracted from the expected output.

Each atomic piece of information is a json object with the following fields:

- "aspect": the atomic piece of information extracted from the expected output.
- "explanation": a brief explanation of why this atomic piece of information is important or relevant to the question.
- "evidence": the evidence from the expected output that supports this atomic piece of information.

# question: {QUESTION}

# expected\_output: {EXPECTED\_OUTPUT}

Your output should be a JSON object enclosed in ```json ``` block in the given format.

Figure 22: 用于从期望输出中提取原子方面的提示，以用于面向召回的碎片正确性奖励模型。

### Matching Aspects for Coverage Reward

You are an impartial judge who has been asked to evaluate how the generated output answers the question. You will be given a question, the expected output, a generated output, and a single aspect that you need to evaluate if the generated output contains the same information about from that aspect point of view. Your task is to compare the generated output and the expected output based on the given aspect. You need to provide a score between -1 and 2 that indicates the degree of match between the two outputs from the aspect point of view, using the following criteria:

# scoring criteria:

2: Correct and relevant (no irrelevant information).

1: Correct but contains irrelevant information.

0: No answer provided (abstention).

-1: Incorrect answer.

# Your input:

- "question": The question that was asked
- "expected\_output": The expected output.
- "generated\_output": The generated output.
- "aspect": The aspect that you need to evaluate the generated output based on it, containing the following fields:
  - "aspect": the atomic piece of information extracted from the expected output.
  - "explanation": a brief explanation of why this atomic piece of information is important or relevant to the question.
  - "evidence": the evidence from the expected output that supports this atomic piece of information.

# your output: you need to provide a JSON object enclosed in ```json ``` that contains the following fields:

- "score": an int indicating the score you assign to the generated output based on the given aspect.
- "rationale": a str indicating the rationale behind your score.

# question: {QUESTION}

# expected\_output: {EXPECTED\_OUTPUT}

# generated\_output: {GENERATED\_OUTPUT}

# aspect: {ASPECT}

Your output should be a JSON object enclosed in ```json ``` block in the given format.

Figure 23: 用于在预期输出和生成响应之间匹配原子方面的提示，以用于面向召回的片段正确性奖励模型。

### Extracting Aspects for Faithfulness Reward

You are an impartial judge who has been asked to evaluate how the generated output is faithful to the supporting documents provided. Your task is to given a generated output for a given question, extract all atomic pieces of information from the generated output. These atomic pieces of information are the smallest units of information that discuss a single unique aspect of the answer to the question.

# Your input:

- "question": The question that was asked
- "answer": The generated answer.

# your output: you need to provide a JSON object enclosed in ``json`` that contains the following fields:

- "answer\_aspects": a list of atomic pieces of information extracted from the generated output. Each atomic piece of information is a json object with the following fields:
  - "id": the id of the atomic piece of information.
  - "aspect": the atomic piece of information extracted from the generated output.
  - "explanation": a brief explanation of why this atomic piece of information is important or relevant to the question.
  - "evidence": the evidence from the generated output that supports this atomic piece of information.

# question: {QUESTION}

# answer: {ANSWER}

Figure 24: 用于从生成的输出中提取原子方面以获得可信度奖励的提示。

### Matching Aspects for Faithfulness Reward

You are an impartial judge who has been asked to evaluate how well the generated answer is grounded in the supporting knowledge provided based on the given criteria. You will be given a list of atomic aspects from the generated output and a list of supporting documents. Your task is to go through each extracted atomic aspect and check if its evidence from the generated output is grounded in the supporting documents. You need to provide a score between -1 and 1 that indicates the degree of match between the two outputs from the aspect point of view, using the following criteria:

- 1: Full support. All answer parts are grounded in the supporting documents.
- 0: Partial support. Not all answer parts are grounded in the supporting documents.
- 1: No support. All answer parts are not grounded in the supporting documents.

# Your input:

- "question": The question that was asked
- "answer\_aspects": a list of atomic pieces of information extracted from the generated output. Each atomic piece of information is a json object with the following fields:
  - "id": the id of the atomic piece of information.
  - "aspect": the atomic piece of information extracted from the generated output.
  - "explanation": a brief explanation of why this atomic piece of information is important or relevant to the question.
  - "evidence": the evidence from the generated output that supports this atomic piece of information.
- "context": The a list of supporting documents that you should check the answer based on.

# your output: you need to provide a JSON object enclosed in ``json`` that contains the following fields:

- "scores\_list": a list of scores for each atomic aspect, indicating the score you assign to the generated answer based on the given criteria. Each object in the list should be a valid json object that contain the following fields:
  - "id": the id of the atomic piece of information.
  - "score": an int indicating the score you assign to the generated answer based on the given criteria.
  - "rationale": a str indicating the rationale behind your score.

# question: {QUESTION}

# answer\_aspects: {ASPECT}

# context: {CONTEXT}

Figure 25: 用于在生成的输出和检索到的文档之间匹配方面以获得真实性奖励的提示。



**Algorithm 4** 忠实性奖励模型的实现。**Input:** question  $q$ , generated response  $r$ , retrieved documents  $C$ , evaluator LLM  $\pi$ **Output:** faithfulness score  $s_f$ 


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```

1:  $extracted\_aspects = \pi(q, r)$                                 ▶ Extracting the atomic aspects from the generated output
2:  $S_f = 0$ 
3: for  $aspect \in extracted\_aspects$  do                            ▶ For each of the extracted aspects from the generated response
4:    $S_{aspect} = \frac{\pi(q, aspect, r, C) + 1}{2}$                     ▶ Score the aspect using the LLM in range of -1 and 1, then normalize it to 0 and 1
5:    $S_f = S_f + \frac{S_{aspect}}{|extracted\_aspects|}$                 ▶ Adding the score of aspect to the final score
6: end for
7: return  $s_f$                                                     ▶ Returning the faithfulness score for the generated response

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Table 2: 对问题 mRAG 的第一个案例研究：安全关注氢气蒸汽重整

Agent	Conversation
Coordinator	<div>User: { "question": "safety concerns hydrogen steam reforming" }</div> <div>LLM: { "agent": "planner", "input": { "question": "safety concerns hydrogen steam reforming", "information": "" }, "reason": "I will use the planner agent to create a strategy for gathering and processing information related to safety concerns associated with hydrogen steam reforming." }</div>
Planner	<div>User (Coordinator): { "question": "safety concerns hydrogen steam reforming","information":"" }</div> <div>LLM (Planner): { "plan": ["Identify the key components of hydrogen steam reforming process", "Research potential safety hazards associated with each component", "Gather data on accidents or incidents related to hydrogen steam reforming from reliable sources such as industry reports, academic journals, and government databases", "Review existing safety guidelines and regulations for hydrogen steam reforming from organizations like OSHA, ISO, or relevant national agencies", "Analyze the risk factors and propose mitigation strategies for identified safety concerns", "Summarize findings and present a comprehensive overview of safety concerns and recommended measures"] }</div>
Coordinator	<div>User(Planner): "Output from Planner [Avoiding Repetition]"</div> <div>LLM: { "agent": "searcher", "input": { "question": "safety concerns hydrogen steam reforming", "information": "", "suggestions": ["key components of hydrogen steam reforming process","potential safety hazards associated with each component","accidents or incidents related to hydrogen steam reforming","existing safety guidelines and regulations for hydrogen steam reforming" ] }, "reason": "The searcher agent will help me find relevant information about the key components of hydrogen steam reforming, potential safety hazards, historical incidents, and current safety guidelines." }</div>

Searcher	<p>User (Coordinator): "Output from Coordinator [Avoiding Repetition]"</p> <hr/> <p>LLM (Searcher): { "search_query": "key components of hydrogen steam reforming process", "search_query_explanation": "To understand the safety concerns of hydrogen steam reforming, it is important to first identify its key components as these components are likely to pose potential safety hazards." }</p> <hr/> <p>User (Retriever): This is the information resulted from your search query:  Query ID: 0  Documnet 1 ID: 552  Document 1 text: Product gas from the steam reforming of the methane and naphtha contains equilibrium amounts of hydrogen,...  Documnet 2 ID: 352  Document 2 text: A final process stream is produced by steam reforming of residual...  Now I need you to verify the information. Be as objective as possible in your verification. Note you should strictly follow the given format and do not add any extra explanation or information to your output.</p> <hr/> <p>LLM (Searcher): { "query_id": 0, "relevance": [ { "doc_id": 552, "is_relevant": true, "is_relevant_explanation": "This document provides detailed information about the key components of the hydrogen steam reforming process, including the reformer, the temperature conditions, and the water-shift gas reactions. It is highly relevant to understanding the safety concerns of the process." }, { "doc_id": 352, "is_relevant": false, "is_relevant_explanation": "This document focuses on the advantages and economic benefits of the steam reforming process but does not provide specific details about the key components or potential safety hazards. Therefore, it is less relevant to the current query." } ], "change_search_query": false, "change_search_query_explanation": "The initial search query yielded relevant documents that provide detailed information about the key components of the hydrogen steam reforming process. No immediate need to change the search query.", "new_search_query": "", "end_search": false, "end_search_explanation": "More information is needed to fully address the safety concerns of the hydrogen steam reforming process. Additional searches may be necessary to find details on potential safety hazards and existing safety guidelines. }</p> <hr/> <p>User (Retriever): This is the information resulted from your search query:  Query ID: 0  Documnet 1 ID: 832  Document 1 text: Steam Methane Reforming one of the greatest challenges in today2019s industries...  Documnet 2 ID: 915  Document 2 text: 5,082,481, Membrane Separation Process for Cracked Gases, describes...  Now I need you to verify the information. Be as objective as possible in your verification. Note you should strictly follow the given format and do not add any extra explanation or information to your output.</p> <hr/> <p>LLM (Searcher): { "query_id": 0, "relevance": [ { "doc_id": 832, "is_relevant": true, "is_relevant_explanation": "This document provides detailed information about the steam methane reforming process, including the temperature and pressure conditions, the role of reformer tubes, and the importance of the process in hydrogen production. It is highly relevant to understanding the safety concerns of the process." }, { "doc_id": 915, "is_relevant": false, "is_relevant_explanation": "This document discusses various membrane technologies for hydrogen recovery but does not provide specific details about the key components or potential safety hazards of the steam methane reforming process. Therefore, it is less relevant to the current query." } ],</p>
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Searcher (Contd.)	<p>"change_search_query": false,  "change_search_query_explanation": "The initial search query yielded relevant documents that provide detailed information about the steam methane reforming process. No immediate need to change the search query.",  "new_search_query": "",  "end_search": false,  "end_search_explanation": "More information is needed to fully address the safety concerns of the steam methane reforming process. Additional searches may be necessary to find details on potential safety hazards and existing safety guidelines." }</p> <hr/> <p>User (Retriever): This is the information resulted from your search query:  Query ID: 0  Documnet 1 ID: 189  Document 1 text: The reformer furnace design alternatives will be discussed below. Feed gas 2014 usually a mixture of hydrogen, methane and other light hydrocarbons 2014 is first compressed to about 300 psig....  Documnet 2 ID: 254  Document 2 text: BRIEF DESCRIPTION OF THE DRAWINGS These and other objects, features and advantages of the present invention will become better understood with regard to the following description, pending claims and accompanying drawings where:....  Now I need you to verify the information. Be as objective as possible in your verification. Note you should strictly follow the given format and do not add any extra explanation or information to your output.</p> <hr/> <p>LLM (Searcher): { "query_id": 0, "relevance": [ { "doc_id": 189,  "is_relevant": true,  "is_relevant_explanation": "This document provides detailed information about the key components of the hydrogen steam reforming process, including the preheating, compression, and heating stages, as well as the role of reformer tubes and furnace designs. It is highly relevant to understanding the safety concerns of the process."  { "doc_id": 254,  "is_relevant": false,  "is_relevant_explanation": "This document focuses on a novel pre-reforming and reforming process configuration involving membranes for hydrogen gas separation and recovery. While it mentions the steam methane reforming process, it does not provide specific details about the key components or potential safety hazards. Therefore, it is less relevant to the current query." } ],  "change_search_query": false,  "change_search_query_explanation": "The initial search query yielded relevant documents that provide detailed information about the key components of the hydrogen steam reforming process. No immediate need to change the search query.",  "new_search_query": "",  "end_search": false,  "end_search_explanation": "More information is needed to fully address the safety concerns of the hydrogen steam reforming process. Additional searches may be necessary to find details on potential safety hazards and existing safety guidelines. }</p> <hr/> <p>User (Retriever): This is the information resulted from your search query:  Query ID: 0  Documnet 1 ID: 985  Document 1 text: Minimizing the hydrogen bled into the fuel gas can keep the hydrogen production levels manageable. However, the hydrogen plant feed usually includes some hydrogen that goes through for a 201cfree ride,...  Documnet 2 ID: 243  Document 2 text: BRIEF DESCRIPTION OF THE DRAWINGS These and other objects, features and advantages of the present invention will become better understood with regard to the following description, pending claims and accompanying drawings where:....</p>
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Searcher (Contd.)	<p>Now I need you to verify the information. Be as objective as possible in your verification. Note you should strictly follow the given format and do not add any extra explanation or information to your output....</p> <hr/> <p>LLM (Searcher): { "query_id": 0, "relevance": [ { "doc_id": 189, "is_relevant": true, "is_relevant_explanation": "This document provides detailed information about the key components of the hydrogen steam reforming process, including the preheating, compression, and heating stages, as well as the role of reformer tubes and furnace designs. It is highly relevant to understanding the safety concerns of the process." }, { "doc_id": 254, "is_relevant": false, "is_relevant_explanation": "This document focuses on a novel pre-reforming and reforming process configuration involving membranes for hydrogen gas separation and recovery. While it mentions the steam methane reforming process, it does not provide specific details about the key components or potential safety hazards. Therefore, it is less relevant to the current query." } ], "change_search_query": false, "change_search_query_explanation": "The initial search query yielded relevant documents that provide detailed information about the key components of the hydrogen steam reforming process. No immediate need to change the search query.", "new_search_query": "", "end_search": false, "end_search_explanation": "More information is needed to fully address the safety concerns of the hydrogen steam reforming process. Additional searches may be necessary to find details on potential safety hazards and existing safety guidelines. } }</p> <hr/> <p>User (Retriever): This is the information resulted from your search query:  Query ID: 0  Documnet 1 ID: 174  Document 1 text: Gas enters the bottom of the absorber, where it contacts lean solution. The carbon dioxide is absorbed from the gas, leaving the rest of the contaminants and hydrogen relatively untouched.....  Documnet 2 ID: 769  Document 2 text: From our extensive range of gas production machinery, we manufacture, export and supply supreme quality Hydrogen Gas Generator.....  Now I need you to verify the information. Be as objective as possible in your verification. Note you should strictly follow the given format and do not add any extra explanation or information to your output.</p> <hr/> <p>LLM (Searcher): { "query_id": 0, "relevance": [ { "doc_id": 174, "is_relevant": false, "is_relevant_explanation": "This document focuses on the PSA (Pressure Swing Adsorption) process for hydrogen purification and does not provide specific details about the key components or potential safety hazards of the steam methane reforming process. Therefore, it is less relevant to the current query." }, { "doc_id": 769, "is_relevant": false, "is_relevant_explanation": "This document describes a hydrogen gas generator and its features but does not provide specific details about the key components or potential safety hazards of the steam methane reforming process. Therefore, it is less relevant to the current query." } ], "change_search_query": true, "change_search_query_explanation": "The documents provided do not contain specific details about the key components or potential safety hazards of the steam methane reforming process. A new search query focusing on safety concerns and potential hazards is needed.", "new_search_query": "potential safety hazards associated with steam methane reforming", "end_search": false, "end_search_explanation": "More information is needed to fully address the safety concerns of the steam methane reforming process. A new search query focusing on potential safety hazards is necessary." }</p>
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Searcher (Contd.)	<p>User (Retriever): This is the information resulted from your search query:  Query ID: 0  Documnet 1 ID: 124  Document 1 text: Gas enters the bottom of the absorber, where it contacts lean solution. The carbon dioxide is absorbed from the gas, leaving the rest of the contaminants and hydrogen relatively untouched.....  Documnet 2 ID: 832  Document 2 text: Steam Methane Reforming one of the greatest challenges in today's industries is an increased demand for hydrogen. Due to its ever-increasing industrial relevance, there is a need for efficient methods of hydrogen production, which has traditionally been done at a high temperature....  Now I need you to verify the information. Be as objective as possible in your verification. Note you should strictly follow the given format and do not add any extra explanation or information to your output.</p> <hr/> <p>LLM (Searcher): { "query_id": 1, "relevance": [ { "doc_id": 124, "is_relevant": true, "is_relevant_explanation": "This document provides detailed information about the potential safety hazards during the startup procedure of steam methane reformers, including the risk of overheating and melting of reformer tubes. It is highly relevant to understanding the safety concerns of the process." }, { "doc_id": 832, "is_relevant": false, "is_relevant_explanation": "This document focuses on the general description of the steam methane reforming process and its importance but does not provide specific details about potential safety hazards. Therefore, it is less relevant to the current query." } ], "change_search_query": false, "change_search_query_explanation": "The initial search query yielded relevant documents that provide detailed information about the potential safety hazards during the steam methane reforming process. No immediate need to change the search query.", "new_search_query": "", "end_search": true, "end_search_explanation": "The provided information is sufficient to address the safety concerns of the steam methane reforming process. Further searches are not necessary." }</p>
Coordinator	<p>User (Searcher): "only the relevant documents found by searcher"</p> <hr/> <p>LLM : { "agent": "reasoner", "input": { "question": "safety concerns hydrogen steam reforming", "information": "Steam methane reforming is a chemical process by which methane is converted to hydrogen. It involves the reaction between natural gas, which contains methane and steam, at a temperature of 700-1000°C and under a pressure of 3-25 bar. The products of this chemical process are initially hydrogen and carbon monoxide. The carbon monoxide is further reacted with steam in a water-gas shift reaction to produce more hydrogen and carbon dioxide. Impurities are then removed from the system using pressure-swing adsorption. As a result, pure hydrogen is isolated and extracted. This process is mediated by reformer tubes also known as catalyst tubes used in steam reformer furnaces known as steam methane reformers. Minimizing the hydrogen bled into the fuel gas can keep the hydrogen production levels manageable. However, the hydrogen plant feed usually includes some hydrogen that goes through for a free ride, except for the cost of heating it up to reformer temperature and ultimately cooling it back down to recovery level." }, "aspect": "Key components of hydrogen steam reforming process" }, "reason": "I will use the reasoner agent to analyze the key components of the hydrogen steam reforming process and identify potential safety concerns associated with each component." }</p>

Reasoner	<p>User (Coordinator): Output from Coordinator [Avoiding Repetition]</p> <hr/> <p>LLM (Reasoner): { "analysis": "Hydrogen steam reforming involves multiple key components including the chemical reaction between methane and steam, the use of reformer tubes or catalyst tubes, and the subsequent purification steps.", "The primary chemical reaction occurs in the steam reformer furnace, where methane reacts with steam at high temperatures (700-1000 u00b0C) and pressures (3-25 bar) to produce hydrogen and carbon monoxide.", "Reformer tubes or catalyst tubes play a crucial role in facilitating the chemical reaction. These tubes house the catalyst necessary for the steam reforming process, enhancing the rate of hydrogen production.", "After the initial reaction, a water-gas shift reaction takes place to further convert carbon monoxide into additional hydrogen and carbon dioxide, improving the purity of the hydrogen output.", "Purification steps such as pressure-swing adsorption are employed to remove impurities from the hydrogen stream, ensuring the final product is of high quality and suitable for various applications.", "Minimizing hydrogen bleed during the process helps maintain efficiency, but some hydrogen inevitably remains in the feed stream, requiring energy to heat and cool." }</p>
Coordinator	<p>User (Reasoner): "Output from Reasoner [Avoiding Repetition]"</p> <hr/> <p>LLM : { "agent": "reasoner",  "input": { "question": "safety concerns hydrogen steam reforming",  "information": "Hydrogen steam reforming involves multiple key components including the chemical reaction between methane and steam, the use of reformer tubes or catalyst tubes, and the subsequent purification steps. The primary chemical reaction occurs in the steam reformer furnace, where methane reacts with steam at high temperatures (700-1000u00b0C) and pressures (3-25 bar) to produce hydrogen and carbon monoxide. Reformer tubes or catalyst tubes play a crucial role in facilitating the chemical reaction. After the initial reaction, a water-gas shift reaction takes place to further convert carbon monoxide into additional hydrogen and carbon dioxide, improving the purity of the hydrogen output. Purification steps such as pressure-swing adsorption are employed to remove impurities from the hydrogen stream, ensuring the final product is of high quality and suitable for various applications. Minimizing hydrogen bleed during the process helps maintain efficiency, but some hydrogen inevitably remains in the feed stream, requiring energy to heat and cool." },  "aspect": "Potential safety hazards associated with each component" },  "reason": "I will use the reasoner agent to identify potential safety hazards associated with each key component of the hydrogen steam reforming process." }</p>

Reasoner	<p>User (Coordinator): Output from Coordinator [Avoiding Repetition]</p> <hr/> <p>LLM (Reasoner): { "analysis": "The steam reformer furnace is a critical component as it operates at extremely high temperatures (700-1000 u00b0C). High temperatures pose potential risks such as thermal stress, cracking, and potential leaks of flammable gases like methane, leading to fire or explosion hazards.", "Reformer tubes or catalyst tubes are another key component. These tubes contain reactive materials that can degrade over time due to exposure to high temperatures and corrosive environments, potentially leading to tube failure and gas leaks. Additionally, the high-pressure environment (3-25 bar) increases the severity of any leaks, posing significant safety risks.", "The water-gas shift reactor, although not explicitly mentioned in the provided information, is an important step in the process. It involves the reaction of carbon monoxide with steam at around 300-400 u00b0C to produce more hydrogen. High temperatures and the presence of reactive gases increase the risk of equipment failure and gas leaks, which could lead to inhalation of toxic gases or fires.", "Pressure-swing adsorption (PSA) is a purification step that uses adsorbents to remove impurities from the hydrogen stream. During the adsorption and desorption cycles, there is a risk of overpressure or vacuum conditions, which can damage the PSA equipment and lead to gas leaks. Furthermore, the handling of adsorbents can pose health risks if inhaled or contacted directly.", "Overall, the high temperatures, pressures, and flammable gases involved in the hydrogen steam reforming process mean that all components must be carefully designed, maintained, and monitored to ensure safety. Any failure in these systems can lead to serious safety hazards." }</p>
Coordinator	<p>User (Reasoner): Output from Reasoner [Avoiding Repetition]</p> <hr/> <p>LLM: { "agent": "searcher", "input": { "question": "safety concerns hydrogen steam reforming", "information": "The steam reformer furnace is a critical component as it operates at extremely high temperatures (700-1000u00b0C). Reformer tubes or catalyst tubes are another key component. The water-gas shift reactor involves high temperatures and the presence of reactive gases. Pressure-swing adsorption (PSA) equipment handles overpressure and vacuum conditions.", "suggestions": [ "Historical incidents related to hydrogen steam reforming", "Existing safety guidelines and regulations for hydrogen steam reforming", "Mitigation strategies for identified safety concerns" ], "reason": "The searcher agent will help me find historical incidents, existing safety guidelines, and mitigation strategies related to hydrogen steam reforming to provide a comprehensive overview of safety concerns and recommended measures." } }</p>



Searcher	<p>LLM (Searcher): { "search_query": "historical incidents related to hydrogen steam reforming", "search_query_explanation": "Historical incidents can provide valuable insights into the types of safety issues that have occurred in the past, which can help identify current safety concerns and potential mitigation strategies." }</p> <hr/> <p>User (Retriever): This is the information resulted from your search query:  Query ID: 2  Documnet 1 ID: 785  Document 1 text: Fuel refineries use a series of chemical reactions to arrive at the final product. Hydrogen fluoride is used in the oil refining process and causes a reaction, called alkylation, to make fuel from unrefined oil....  Documnet 2 ID: 200  Document 2 text: Fig. 4: Mass fractions of the species (ethanol, CO2 and H2O) along the reformer axis. The mass fractions of the ethanol and steam decay along the reformer axis. The ethanol conversion is 80.3 % .....  Now I need you to verify the information. Be as objective as possible in your verification. Note you should strictly follow the given format and do not add any extra explanation or information to your output.</p> <hr/> <p>LLM (Searcher): { "query_id": 2, "relevance": [ { "doc_id": 785, "is_relevant": true, "is_relevant_explanation": "This document provides a historical incident related to a refinery accident involving hydrofluoric acid, which can be linked to safety concerns in steam reforming processes. It highlights the potential for catastrophic impacts and the importance of safety protocols." }, { "doc_id": 200, "is_relevant": false, "is_relevant_explanation": "This document discusses the mass fractions of species in a steam reformer and safety concerns related to hydrogen integrity in steel tubes. While it provides technical details, it does not directly address historical incidents or safety guidelines specific to steam reforming. Therefore, it is less relevant to the current query." } ], "change_search_query": false, "change_search_query_explanation": "The initial search query yielded relevant documents that provide a historical incident related to a refinery accident involving hydrofluoric acid, which can be linked to safety concerns in steam reforming processes. No immediate need to change the search query.", "new_search_query": "", "end_search": true, "end_search_explanation": "The provided information is sufficient to address the safety concerns of the steam methane reforming process. Further searches are not necessary." }</p>
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Coordinator	<p>User (Searcher): "only the relevant documents found by searcher"</p> <hr/> <p>LLM (Coordinator): { "agent": "summarizer",  "input": { "question": "safety concerns hydrogen steam reforming",  "information": "" }  "The steam reformer furnace is a critical component as it operates at extremely high temperatures (700-1000°C). Reformer tubes or catalyst tubes are another key component. The water-gas shift reactor involves high temperatures and the presence of reactive gases. Pressure-swing adsorption (PSA) equipment handles overpressure and vacuum conditions. Historical incidents related to hydrogen steam reforming include an explosion at an ExxonMobil refinery in Torrance, California, where an explosion occurred due to a leak of hydrocarbons into an electrostatic precipitator (ESP) device, causing sparks and igniting the hydrocarbons. This resulted in a dust cloud extending for miles and projected large debris around the site. The incident highlighted the importance of proper evaluation of process hazards, implementation of safeguards, and adherence to safety precautions." }  "reason": "I will use the summarizer agent to create a concise summary of the key points regarding the safety concerns associated with hydrogen steam reforming based on the gathered information." }</p>
Summarizer	<p>User (Coordinator): Output from Coordinator and relevant retrieved documents [Avoiding Repetition]</p> <hr/> <p>LLM (Summarizer): { "summary": "Hydrogen steam reforming involves critical components like high-temperature furnaces (700-1000 °C), reformer/tubes, and water-gas shift reactors. PSA equipment manages overpressure/vacuum conditions. Historical incidents, such as an explosion at ExxonMobil's 2019s Torrance refinery, underscore the need for thorough hazard assessments, robust safety measures, and strict adherence to safety protocols." }</p>
Coordinator	<p>User (Answerer): Output from Summarizer [Avoiding Repetition]</p> <hr/> <p>LLM: { "agent": "Answerer",  "input": { "question": "safety concerns hydrogen steam reforming",  "guidance": "Provide a detailed overview of the key components of hydrogen steam reforming, potential safety hazards associated with each component, historical incidents, and existing safety guidelines and regulations.",  "important_information": "High-temperature furnaces (700-1000°C), reformer/tubes, water-gas shift reactors, PSA equipment, historical incidents, and safety guidelines." }  "reason": "I will use the answerer agent to generate a comprehensive response to the question about safety concerns in hydrogen steam reforming, incorporating the key components, potential hazards, historical incidents, and safety guidelines." },</p>
Answerer	<p>User (Coordinator): Output from Coordinator [Avoiding Repetition]</p> <hr/> <p>LLM: { "response": "Hydrogen steam reforming is a critical process in the production of hydrogen, involving several key components such as high-temperature furnaces, reformer/tubes, water-gas shift reactors, and PSA equipment. Each component presents specific safety concerns. High-temperature furnaces, operating at 700-1000 °C, pose risks of thermal burns and potential tube failures due to excessive temperatures. Reformer/tubes are susceptible to coking and require careful monitoring to prevent catalyst degradation. Water-gas shift reactors, where the exothermic reaction occurs, need proper cooling systems to manage temperature increases. PSA equipment, used for hydrogen purification, must be handled with care to avoid pressure-related accidents. Historical incidents, such as the ExxonMobil refinery explosion involving hydrofluoric acid, highlight the importance of stringent safety measures. Safety guidelines emphasize the need for proper monitoring, regular maintenance, and adherence to operating procedures to mitigate risks. Regulations require thorough hazard assessments and the implementation of safeguards to prevent accidents. Understanding these components and their associated safety concerns is crucial for the safe operation of hydrogen steam reforming facilities." }</p>

Coordinator	<p>User (Answerer): Output from Answerer [Avoiding Repetition]</p> <hr/> <p>LLM: { "agent": "validator", "input": { "question": "safety concerns hydrogen steam reforming" "information": "Hydrogen steam reforming is a critical process in the production of hydrogen, involving several key components such as high-temperature furnaces, reformer/tubes, water-gas shift reactors, and PSA equipment. Each component presents specific safety concerns. High-temperature furnaces, operating at 700-100000b0C, pose risks of thermal burns and potential tube failures due to excessive temperatures. Reformer/tubes are susceptible to coking and require careful monitoring to prevent catalyst degradation. Water-gas shift reactors, where the exothermic reaction occurs, need proper cooling systems to manage temperature increases. PSA equipment, used for hydrogen purification, must be handled with care to avoid pressure-related accidents. Historical incidents, such as the ExxonMobil refinery explosion involving hydrofluoric acid, highlight the importance of stringent safety measures. Safety guidelines emphasize the need for proper monitoring, regular maintenance, and adherence to operating procedures to mitigate risks. Regulations require thorough hazard assessments and the implementation of safeguards to prevent accidents. Understanding these components and their associated safety concerns is crucial for the safe operation of hydrogen steam reforming facilities.", "response": "Hydrogen steam reforming is a critical process in the production of hydrogen, involving several key components such as high-temperature furnaces, reformer/tubes, water-gas shift reactors, and PSA equipment. Each component presents specific safety concerns. High-temperature furnaces, operating at 700-100000b0C, pose risks of thermal burns and potential tube failures due to excessive temperatures. Reformer/tubes are susceptible to coking and require careful monitoring to prevent catalyst degradation. Water-gas shift reactors, where the exothermic reaction occurs, need proper cooling systems to manage temperature increases. PSA equipment, used for hydrogen purification, must be handled with care to avoid pressure-related accidents. Historical incidents, such as the ExxonMobil refinery explosion involving hydrofluoric acid, highlight the importance of stringent safety measures. Safety guidelines emphasize the need for proper monitoring, regular maintenance, and adherence to operating procedures to mitigate risks. Regulations require thorough hazard assessments and the implementation of safeguards to prevent accidents. Understanding these components and their associated safety concerns is crucial for the safe operation of hydrogen steam reforming facilities." } , "reason": "I will use the validator agent to check if the generated response meets the criteria for the given question." }</p>
Validator	<p>User (Coordinator): Output from Coordinator [Avoiding Repetition]</p> <hr/> <p>LLM: { "extracted_criteria": [ { "criteria": "detailed", "criteria_explanation": "The question asks about safety concerns related to hydrogen steam reforming, which requires a detailed explanation.", "is_response_valid": true, "is_response_valid_feedback": "The response is detailed and covers various aspects of safety concerns in hydrogen steam reforming." } ], "is_groundedly_supported": true, "is_groundedly_supported_feedback": "The response is well-grounded with supporting information, including specific components, potential risks, and historical incidents.", "is_correctly_answered": true, "is_correctly_answered_feedback": "The response correctly addresses the safety concerns of hydrogen steam reforming and provides relevant details." } }</p>
Coordinator	<p>User (Validator): Output from Validator [Avoiding Repetition]</p> <hr/> <p>LLM: { "agent": "finisher", "input": "finished":true }</p>

**Table 3:** 第二个关于 mRAG 的问题研究：约翰·鲍尔如何影响霍伊莱克的高尔夫球历史，以及该球场在界外的问题上提出了哪些战略挑战？

Agent	Conversation
Coordinator	<div>User: { "question": "How did John Ball influence golf history at Hoylake, and what strategic challenges does the course present regarding out of bounds?" }</div> <div>LLM: { "agent": "planner", "input": { "question": "How did John Ball influence golf history at Hoylake, and what strategic challenges does the course present regarding out of bounds?", "information": "" }, "reason": "I need to create a plan to gather and organize the necessary information to answer the question." }</div>
Planner	<div>User (Coordinator): { "question": "How did John Ball influence golf history at Hoylake, and what strategic challenges does the course present regarding out of bounds?" "information": "" }</div> <div>LLM (Planner): { "plan": [ "Research John Ball's role in golf history, focusing on his connection to Hoylake Golf Club.", "Identify key events or moments in John Ball's career at Hoylake that significantly impacted golf history.", "Analyze the current layout and characteristics of the Hoylake course, particularly its out of bounds (OB) rules and challenges it presents to players.", "Consult historical records and expert opinions to understand how these OB rules have evolved over time and their impact on gameplay.", "Compile findings into a coherent narrative that highlights John Ball's influence and the strategic challenges posed by the course." ] }</div>
Coordinator	<div>User(Planner): "Output from Planner [Avoiding Repetition]"</div> <div>LLM: { "agent": "searcher", "input": { "question": "How did John Ball influence golf history at Hoylake, and what strategic challenges does the course present regarding out of bounds?", "information": "", "suggestions": [ "John Ball", "Hoylake Golf Club", "history of golf at Hoylake", "out of bounds rules in golf" ], "reason": "The next step is to find relevant information about John Ball's connection to Hoylake and the characteristics of the Hoylake course." }</div>



Searcher	<p>User (Coordinator): "Output from Coordinator [Avoiding Repetition]"</p> <hr/> <p>LLM (Searcher): { "search_query": "John Ball influence on Hoylake golf history",  "search_query_explanation": "This search query aims to find information specifically related to how John Ball influenced golf history at Hoylake, which directly addresses part of the question." }</p> <hr/> <p>User (Retriever): This is the information resulted from your search query:  Query ID: 0  Documnet 1 ID: 224  Document 1 text: United Kingdom: Grant Books, 2001. 81p. half leather, slipcase. Limited edition of 95 subscribers copies. Hoylake, otherwise known as The Royal Liverpool Golf Club is one of golf's most storied venues....  Documnet 2 ID: 705 Document 2 text: Ball dominated amateur golf in Great Britain. He won all the important golf championships as well as the hearts and respect of his country....  Now I need you to verify the information. Be as objective as possible in your verification. Note you should strictly follow the given format and do not add any extra explanation or information to your output.</p> <hr/> <p>LLM (Searcher): { "query_id": 0, "relevance": [ { "doc_id": 224,  "is_relevant": true,  "is_relevant_explanation": "This document mentions John Ball's connection to Hoylake and his influence on golf history, making it relevant to the question."  { "doc_id": 705,  "is_relevant": true,  "is_relevant_explanation": "This document also discusses John Ball's influence on golf history and his relationship with Hoylake, making it relevant to the question." } ],  "change_search_query": false,  "change_search_query_explanation": "The current documents are relevant and contain useful information about John Ball's influence on golf at Hoylake.",  "new_search_query": "",  "end_search": true,  "end_search_explanation": "The provided documents are sufficient to answer the question about John Ball's influence on golf history at Hoylake." }</p>
Coordinator	<p>User (Searcher): "only the relevant documents found by searcher"</p> <hr/> <p>LLM : { "agent": "reasoner",  "input": { "question": "How did John Ball influence golf history at Hoylake, and what strategic challenges does the course present regarding out of bounds?",  "information": ""John Ball, Jr. was born in Hoylake, Cheshire and grew up playing golf on the Royal Liverpool course. He won several Amateur and Open Championships, including the 1890 Open Championship. He was known for his graceful swing and refusal to use a niblick. In 1878, he competed in his first Open Championship and finished fourth at Prestwick." },  "aspect": "John Ball's influence on golf history at Hoylake" },  "reason": "I need to analyze the information I've gathered to determine how John Ball influenced golf history at Hoylake." }</p>

Reasoner	<p>User (Coordinator): Output from Coordinator [Avoiding Repetition]</p> <hr/> <p>LLM (Reasoner): { "analysis": "John Ball, Jr. was born and raised in Hoylake, making him a local figure associated with the Royal Liverpool Golf Club, which is located there.", "He had significant success in golf competitions, winning multiple Amateur and Open Championships, with the most notable being the 1890 Open Championship. This highlights his skill and impact on the sport.", "His participation in the 1878 Open Championship at Prestwick, even before winning the major title, indicates his early prominence in professional golf and his potential influence on the tournament's legacy.", "Ball's graceful swing and refusal to use a niblick (an early type of iron club) reflect his unique style and contributed to his reputation as a skilled player, potentially influencing other golfers' techniques and preferences over time.", "Given his connection to Hoylake and the Royal Liverpool Golf Club, Ball likely played the course extensively, contributing to its historical significance and possibly offering insights or suggestions that shaped the venue's development and reputation." }</p>
Coordinator	<p>User (Reasoner): "Output from Reasoner [Avoiding Repetition]"</p> <hr/> <p>LLM : { "agent": "searcher",  <input": "how="" "question":="" and="" at="" ball="" bounds?",<br="" challenges="" course="" did="" does="" golf="" history="" hoylake,="" influence="" john="" of="" out="" present="" regarding="" strategic="" the="" what="" {=""></input":> "information": "John Ball, Jr. was born and raised in Hoylake, making him a local figure associated with the Royal Liverpool Golf Club, which is located there. He had significant success in golf competitions, winning multiple Amateur and Open Championships, with the most notable being the 1890 Open Championship. His participation in the 1878 Open Championship at Prestwick, even before winning the major title, indicates his early prominence in professional golf and his potential influence on the tournament's legacy. Ball's graceful swing and refusal to use a niblick reflect his unique style and contributed to his reputation as a skilled player, potentially influencing other golfers' techniques and preferences over time. Given his connection to Hoylake and the Royal Liverpool Golf Club, Ball likely played the course extensively, contributing to its historical significance and possibly offering insights or suggestions that shaped the venue's development and reputation." },  "suggestions": [ "strategic challenges of Hoylake course", "out of bounds rules in golf", "Royal Liverpool Golf Club history"],  "reason": "I need to find more information about the strategic challenges presented by the Hoylake course and the specific rules related to out of bounds to complete the analysis." }</p>

Searcher	<p>User (Coordinator): Output from Coordinator [Avoiding Repetition]</p> <hr/> <p>LLM (Searcher): { "search_query": "strategic challenges of Hoylake course", "search_query_explanation": "This search query aims to find information about the strategic challenges presented by the Hoylake course, which is crucial for understanding the second part of the question." }</p> <hr/> <p>User (Retriever): This is the information resulted from your search query: Query ID: 1 Documnet 1 ID: 399 Document 1 text: The old seventeenth, now the first, known as the Royal hole, was one of Harry Colt2019s most famous creations, with the green set right against Stanley Road; sadly, because it was impossible to get spectators round it, the green had to go to get the Open back to Hoylake.... Documnet 2 ID: 829 Document 2 text: The Open requires mental strength to overcome the obstacles thrown by Mother Nature. Having excellent control of ball flight is essential for any player to be successful when playing in windy, rainy and cold conditions..... Now I need you to verify the information. Be as objective as possible in your verification. Note you should strictly follow the given format and do not add any extra explanation or information to your output.</p> <hr/> <p>LLM (Searcher): { "query_id": 1, "relevance": [ { "doc_id": 399, "is_relevant": true, "is_relevant_explanation": "This document discusses the strategic challenges of various golf courses, including Hoylake, particularly focusing on the use of out of bounds lines and bunkers to create strategic elements." } { "doc_id": 829, "is_relevant": false, "is_relevant_explanation": "This document focuses on the mental and physical preparation for playing in difficult weather conditions and does not discuss the strategic challenges of Hoylake or out of bounds rules." } ], "change_search_query": false, "change_search_query_explanation": "The current documents are relevant and contain useful information about John Ball's influence on golf at Hoylake.", "new_search_query": "", "end_search": true, "end_search_explanation": "The provided documents are sufficient to answer the question about John Ball's influence on golf history at Hoylake." }</p> <hr/> <p>User (Retriever): This is the information resulted from your search query: Query ID: 2 Documnet 1 ID: 206 Document 1 text: But it is important to note that, when older courses were built, the penalty for going out of bounds was not necessarily quite as severe as it is today. Back in the day, the use of out of bounds as a strategic hazard was, if not exactly commonplace, far from unknown.... Documnet 2 ID: 399 Document 2 text: The old seventeenth, now the first, known as the Royal hole, was one of Harry Colt2019s most famous creations, with the green set right against Stanley Road; sadly, because it was impossible to get spectators round it, the green had to go to get the Open back to Hoylake...</p> <hr/> <p>LLM (Searcher): { "query_id": 2, "relevance": [ { "doc_id": 206, "is_relevant": true, "is_relevant_explanation": "This document discusses the strategic use of out of bounds at Hoylake, providing specific examples and insights into how the course utilizes these areas." } { "doc_id": 399, "is_relevant": true, "is_relevant_explanation": "This document also provides detailed information about the strategic use of out of bounds at Hoylake, including examples like the Royal hole and the ninth hole (formerly the seventh)." } ], "change_search_query": false, "change_search_query_explanation": "Both documents are relevant and contain useful information about the strategic challenges of Hoylake's course, particularly concerning out of bounds lines." }</p>
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Coordinator	<p>User (Searcher): "only the relevant documents found by searcher"</p> <hr/> <p>LLM: { "agent": "answerer", "input": { "question": "How did John Ball influence golf history at Hoylake, and what strategic challenges does the course present regarding out of bounds?", "guidance": "Provide a detailed account of John Ball's influence on golf at Hoylake, highlighting his achievements and unique style. Also, describe the strategic challenges presented by the Hoylake course, particularly focusing on the out of bounds rules and how they affect gameplay." "important_information": "John Ball's connection to Hoylake, his golfing achievements, and the course's out of bounds rules." "reason": "Based on the gathered information, I will now craft a comprehensive response addressing both aspects of the question." } }</p>
Answerer	<p>User (Coordinator): Output from Coordinator and relevant retrieved documents [Avoiding Repetition]</p> <hr/> <p>LLM (Answerer): { "response": "John Ball significantly influenced golf history at Hoylake, Cheshire, where he grew up playing on the Royal Liverpool Golf Club course. Born in Hoylake, Ball was the son of the Royal Hotel's prosperous owner, which placed him in the heart of the golfing community. His achievements include winning the Open Championship in 1890 and the Amateur Championship in 1888, making him the first English-born player to win both titles in the same year. Ball's unique style was characterized by his graceful swing and his refusal to use a niblick, which he considered 'another bloody spade.' This stubbornness and determination made him a formidable player in match play. Hoylake, known for its storied golfing history, presents strategic challenges, particularly concerning out of bounds rules. The course's design incorporates out of bounds lines as strategic hazards, encouraging players to take risks for better shot lines. For instance, the traditional opening hole features a drive over a turf 'cop,' with the favored strategic line being close to the cop. The use of out of bounds as a strategic element adds complexity to the game, requiring players to balance risk and reward. Overall, John Ball's influence on golf at Hoylake is marked by his exceptional achievements and his impact on the strategic design of the course, particularly through the thoughtful integration of out of bounds rules." } }</p>



Coordinator	<p>User (Answerer): Output from Answerer [Avoiding Repetition]</p> <hr/> <p>LLM: { "agent": "validator", "input": { "question": "How did John Ball influence golf history at Hoylake, and what strategic challenges does the course present regarding out of bounds?" "information": "John Ball significantly influenced golf history at Hoylake, Cheshire, where he grew up playing on the Royal Liverpool Golf Club course. Born in Hoylake, Ball was the son of the Royal Hotel's prosperous owner, which placed him in the heart of the golfing community. His achievements include winning the Open Championship in 1890 and the Amateur Championship in 1888, making him the first English-born player to win both titles in the same year. Ball's unique style was characterized by his graceful swing and his refusal to use a niblick, which he considered 'another bloody spade.' This stubbornness and determination made him a formidable player in match play. Hoylake, known for its storied golfing history, presents strategic challenges, particularly concerning out of bounds rules. The course's design incorporates out of bounds lines as strategic hazards, encouraging players to take risks for better shot lines. For instance, the traditional opening hole features a drive over a turf 'cop,' with the favored strategic line being close to the cop. The use of out of bounds as a strategic element adds complexity to the game, requiring players to balance risk and reward. Overall, John Ball's influence on golf at Hoylake is marked by his exceptional achievements and his impact on the strategic design of the course, particularly through the thoughtful integration of out of bounds rules.", "response": "John Ball significantly influenced golf history at Hoylake, Cheshire, where he grew up playing on the Royal Liverpool Golf Club course. Born in Hoylake, Ball was the son of the Royal Hotel's prosperous owner, which placed him in the heart of the golfing community. His achievements include winning the Open Championship in 1890 and the Amateur Championship in 1888, making him the first English-born player to win both titles in the same year. Ball's unique style was characterized by his graceful swing and his refusal to use a niblick, which he considered 'another bloody spade.' This stubbornness and determination made him a formidable player in match play. Hoylake, known for its storied golfing history, presents strategic challenges, particularly concerning out of bounds rules. The course's design incorporates out of bounds lines as strategic hazards, encouraging players to take risks for better shot lines. For instance, the traditional opening hole features a drive over a turf 'cop,' with the favored strategic line being close to the cop. The use of out of bounds as a strategic element adds complexity to the game, requiring players to balance risk and reward. Overall, John Ball's influence on golf at Hoylake is marked by his exceptional achievements and his impact on the strategic design of the course, particularly through the thoughtful integration of out of bounds rules." } , "reason": "I need to validate if the response accurately addresses the question and is grounded in the provided information." }</p>
Validator	<p>User (Coordinator): Output from Coordinator [Avoiding Repetition]</p> <hr/> <p>LLM (Validator): { "extracted_criteria": [ { "criteria": "detailed", "criteria_explanation": ""The question asks about John Ball's influence on golf history at Hoylake and the strategic challenges presented by the course. A detailed response would cover these aspects comprehensively.", "is_response_valid": true, "is_response_valid_feedback": "The response is detailed and covers both the historical influence of John Ball and the strategic challenges presented by the course." } ], "is_groundedly_supported": true, "is_groundedly_supported_feedback": "The response is well-grounded in the provided information and includes specific examples such as the Open Championship wins and the strategic use of out of bounds lines.", "is_correctly_answered": true, "is_correctly_answered_feedback": "The response correctly answers the question by detailing John Ball's influence and explaining the strategic challenges presented by Hoylake." } }</p>

Coordinator	User (Validator): Output from Validator [Avoiding Repetition]
	LLM: { "agent": "finisher", "input": "finished": true }