TOWARD CYBERSECURITY-EXPERT SMALL LANGUAGE MODELS

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ABSTRACT

Large language models (LLMs) are transforming everyday applications, yet deployment in cybersecurity lags due to a lack of high-quality, domain-specific models and training datasets. To address this gap, we present CyberPal 2.0, a family of cybersecurity-expert small language models (SLMs) ranging from 4B–20B parameters. To train CyberPal 2.0, we generate an enriched chain-of-thought cybersecurity instruction dataset built with our data enrichment and formatting pipeline, SecKnowledge 2.0, which integrates expert-in-the-loop steering of reasoning formats alongside LLM-driven multi-step grounding, yielding higher-fidelity, task-grounded reasoning traces for security tasks. Across diverse cybersecurity benchmarks, CyberPal 2.0 consistently outperforms its baselines and matches or surpasses various open and closed-source frontier models, while remaining a fraction of their size. On core cyber threat intelligence knowledge tasks, our models outperform almost all tested frontier models, ranking second only to Sec-Gemini v1. On core threat-investigation tasks, such as correlating vulnerabilities and bug tickets with weaknesses, our best 20B-parameter model outperforms GPT-4o, o1, o3-mini, and Sec-Gemini v1, ranking first, while our smallest 4B-parameter model ranks second.

1 INTRODUCTION

Language models have the potential to reshape cybersecurity across the stack, from vulnerability triage to code and malware analysis. One of the most promising areas for practical impact is threat management and security operations (Motlagh et al., 2024; Yao et al., 2024). This encompasses correlating heterogeneous telemetry across endpoints, networks, cloud, and application sources; prioritizing and summarizing incidents; hypothesis-driven investigations; and recommending response actions and playbooks (Zhang et al., 2025a; Lin et al., 2025). This paper focuses on that direction, proposing a single defensive model that encompasses the entire security operations loop. The goal is to create a domain-specialized backbone that delivers the core capabilities for detection, investigation, response, threat hunting, and data classification, while remaining straightforward to integrate and deploy in enterprise pipelines.

However, adopting frontier models for security is a challenging task. Commercial offerings typically enforce strict safety guardrails, which limit their practical utility in real-world security workflows (Weerawardhena et al., 2025). Additionally, full integration with organizational data sources is further constrained by compliance requirements, as security telemetry often contains highly sensitive and private information (Zhang et al., 2025b). For these reasons, many enterprises require on-premises solutions to meet privacy, compliance, and data residency obligations, making it impractical to send sensitive telemetry to external frontier services. These constraints make security another domain where domain-specific Small Language Models (SLMs) are preferable to general-purpose frontier models (Belcak et al., 2025).

In addition to practical deployability, such a model must support core capabilities in the cybersecurity domain. It requires deep technical grounding across multiple domains: operating systems, computer networks, cloud platforms, identity and access management, and enterprise security controls (Li & Liu, 2021; Aslan et al., 2023). Such a model should also understand organizational

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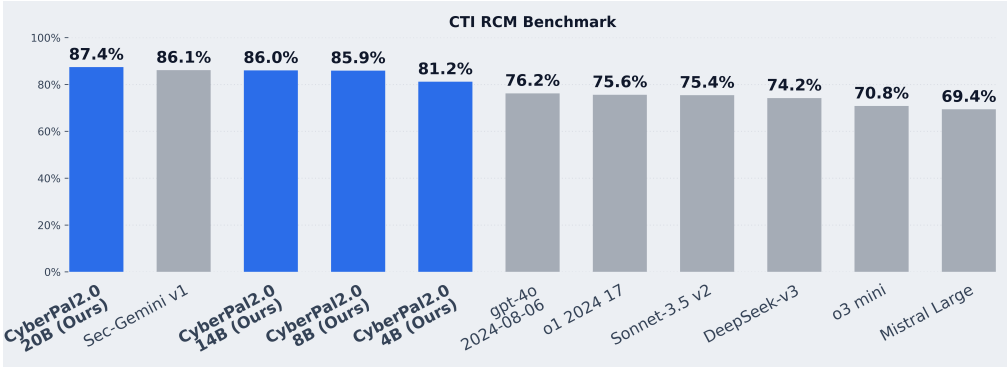
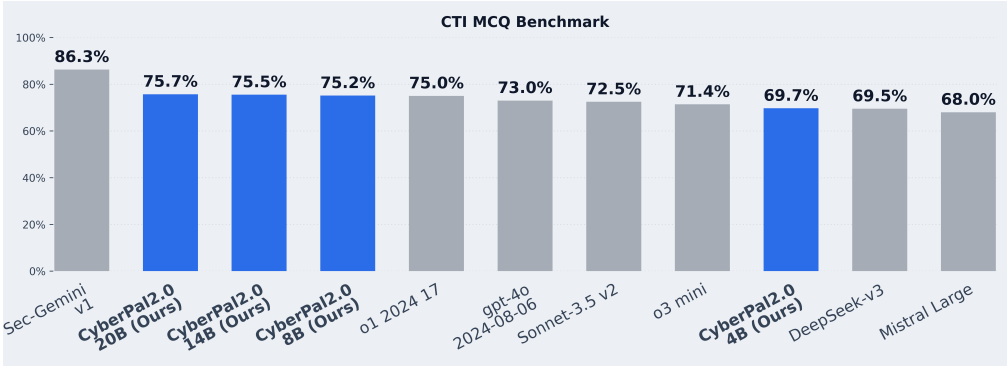


(a) Evaluation results on weaknesses Root Cause Mapping (RCM) tasks.



(b) Evaluation results on core cyber threat intelligence knowledge tasks.

Figure 1: Comparing our models (blue) against frontier models such as Sec-Gemini v1, o1, and o3-mini (gray) on key benchmarks.

security monitoring and visibility, including how to interpret and digest telemetry from diverse systems. Most importantly, the model needs to incorporate comprehensive understanding of threats that includes attacker tactics, techniques, and procedures (TTPs), as well as software vulnerabilities, configuration weaknesses, adversary tooling, and probable attack paths. It must also align with security operation workflows, covering hypothesis-driven threat hunting, investigation, severity assessment, and generation of precise detection and remediation steps. Finally, such a model must connect the dots across these domains, reason effectively over partial and noisy evidence, and deliver defensible conclusions that are accurate and reliable for mission-critical decisions.

In earlier work Levi et al., took an initial step in this direction. They introduced SecKnowledge, a domain-knowledge-driven cybersecurity instruction dataset built through a multi-phase generation process anchored in expert curation, along with SecKnowledge-Eval, a comprehensive evaluation suite covering a wide range of cybersecurity tasks. Models fine-tuned on SecKnowledge demonstrated significant improvements over baseline methods, highlighting the effectiveness of expert-guided instruction design and domain-specific evaluation in advancing cybersecurity LLMs.

In this paper, we take a substantial step toward a practical security model for threat management and security operations:

- **SecKnowledge 2.0.** We propose a dataset enrichment pipeline that incorporates domain expertise via expert-in-the-loop schema-driven formatting, and applies multi-source, multi-step grounding to improve reasoning traces for security tasks and overall data quality.
- **Suite of cybersecurity-expert SLMs.** We train a suite of cybersecurity-focused SLMs, ranging from 4B to 20B parameters, that reason over complex threats and map domain knowledge to setting-specific analyses and recommendations.
- **Frontier cybersecurity performance.** Across rigorous cybersecurity benchmarks, our SLMs consistently outperform their baselines and state-of-the-art open-source models,

yielding 7–14% average gains; on core cybersecurity threat intelligence (CTI) benchmarks, our models match or surpass frontier closed models (e.g., Sec-Gemini v1, OpenAI's o1), all while retaining the cost efficiency, openness, and on-premises deployability required by enterprises.

2 Related Work

Recent work positions LLMs as security tools across Cyber Threat Intelligence (CTI), malware analysis, and incident response, among other security tasks. Recent systematic reviews synthesize both the landscape and open gaps in evaluation and datasets (Zhang et al., 2025b; Xu et al., 2024). In this work, we focus primarily on using LLMs as security tools and evaluate their performance in applied security settings.

Yu et al. curates a multi-source cybersecurity corpus for pre-training (web content, blogs, books, Wikipedia, and MITRE-linked resources), filters a general crawl for security-related text, and augments it with LLM-style rewrites; it then performs instruction fine-tuning on real-life cybersecurity-oriented tasks with LLM-generated references and distills reasoning on CTI-Bench using a general-purpose model with chain-of-thought. Despite the breadth of the pre-training data, their fine-tuning dataset is limited in size and is derived primarily via distillation. Following this work, Weerawardhena et al. created an instruction-tuned, security-specialized chat model built on the Foundation-Sec-8B base (a Llama-3.1-8B continued-pretrained on a curated cybersecurity corpus), which is competitive with closed models such as Gemma Team et al. and GPT-4o-mini (Hurst et al., 2024). The work minimizes security-specific content during post-training, relying on continued pre-training for domain knowledge; their post-training data emphasize diversity and instruction-following rather than security knowledge injection. Taken together, these studies emphasize security-focused pretraining, leaving underexplored the role of expert-driven, document-grounded supervised fine-tuning, which is crucial not only for reliability but also for enabling practical problem-solving and actionable guidance for cybersecurity workflows Zhang et al. (2025b).

Few practitioner-built checkpoints appear on community hubs (e.g., Hugging Face) without an accompanying paper or technical report (DeepHat-V1; SegoLily Labs). These releases often omit essential details (e.g., training data sources), making rigorous comparison and reproducibility challenging. Closed vendor security models sometimes likewise report only headline scores. Google's Sec-Gemini v1 (Bursztein & Tishchenko, 2025) Combines Gemini's reasoning with security knowledge and tools by tying in Google Threat Intelligence (Mandiant/GTI) and OSV[1]. They report strong results on CTI core knowledge and root-cause mapping tasks, though access remains limited.

We build upon SecKnowledge introduced by Levi et al., which takes a data-first route with an expert instruction set and an evaluation suite, and reported sizable improvements in threat-hunting Q&A and investigation assistance.

3 SecKnowledge 2.0: Data Reformatting and Enrichment Pipeline

In this section, we introduce *SecKnowledge 2.0* - an enhanced version of *SecKnowledge*, a comprehensive cybersecurity instruction dataset originally introduced by Levi et al., which generates synthetic data from curated cybersecurity seed sets. *SecKnowledge 2.0* extends *SecKnowledge* via a reformatting and enrichment pipeline, shown to improve downstream task performance (Fan et al., 2024; Nguyen et al., 2025; Abdin et al., 2024).

This section is organized as follows: Section 3.1 introduces *SecKnowledge*, which serves as our starting point dataset. Section 3.2 describes standard data reformatting and enrichment approaches. Section 3.3 then presents our improvements on top of the standard approaches described in 3.2, which combine LLMs with expert-in-the-loop feedback to define reasoning structures and employs LLM-automated query generation to retrieve external evidence for enriched, reliable responses. We use gpt-oss-120b with *Medium* reasoning effort as the backbone LLM. The result is *SecKnowledge 2.0*, a dataset whose responses are structured, interpretable, and supported by evidence.

[1] https://www.mandiant.com/, https://osv.dev/

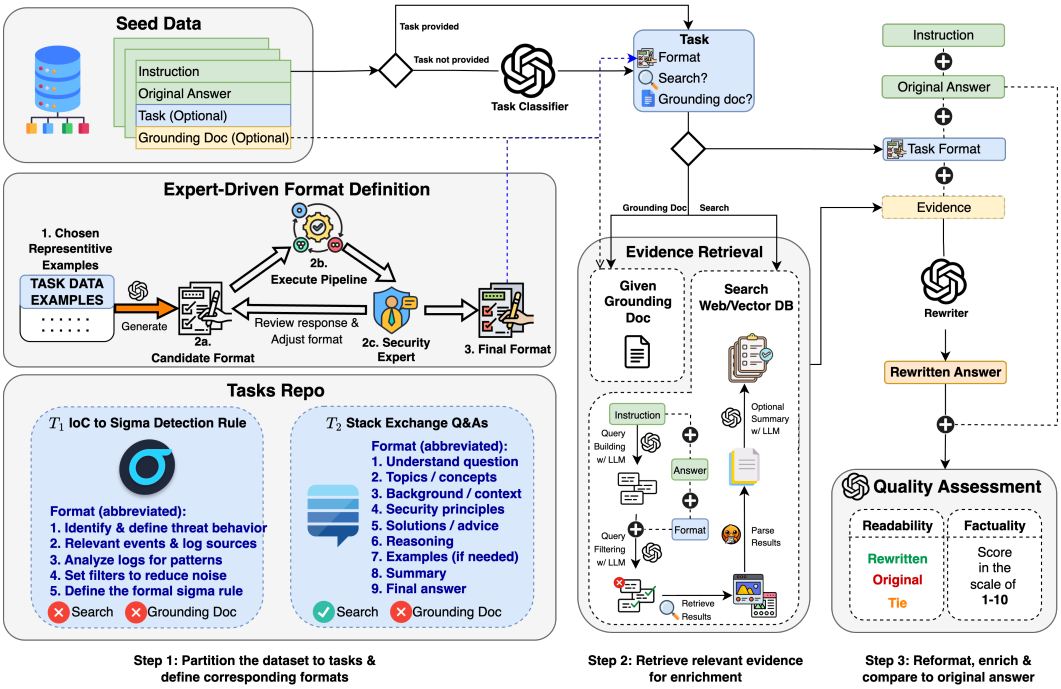


Figure 2: 3-step reformatting and enrichment pipeline overview - experts define task formats for the seed dataset, relevant evidence is retrieved from documents or web sources, answers are reformatted and enriched into structured, knowledge-grounded outputs with LLMaaJudge verification (see A.2).

3.1 SecKnowledge: A Diverse Set of Cybersecurity Instructions Set

SecKnowledge is a domain-knowledge–driven instruction dataset for cybersecurity, constructed in two stages that combine expert curation with structured automation. In the first stage, schema-based parsers were designed for foundational security corpora from public security data sources. In the second stage, SecKnowledge was then extended by generating high-quality seed instructions that capture both per data-source concepts and cross data-source relationships using a novel synthetic data generation method. For example, paths in BRON (a graph that interconnects security entities introduced in Hemberg et al. (2021)) are transformed into chain-of-thought (CoT) Wei et al. (2022) rationales. Sigma rules are converted into step-by-step "how to detect" explanations, and SIEM rules are mapped to ATT&CK TTPs with grounded rationale. First stage yields ∼153k instructions across sources, providing a structurally diverse and practically grounded seed set. In the second stage, *SecKnowledge* increased both diversity and difficulty through dynamic content-grounded synthetic generation, yielding a 403k-example cyber-security corpus.

While *SecKnowledge* provides broad coverage and high-quality supervision, instruction families are intentionally template-based, which can yield limited rationales and shorter reasoning chains. Building on this foundation, our work enriches those items with explicit, step-by-step trajectories and stronger grounding by composing and adapting data reformatting and enrichment methods to the security domain, culminating in **SecKnowledge 2.0**.

3.2 Baseline: Data Reformatting and Enrichment Pipeline

We build on prior work showing that reformatting existing data sources, conditioned on chain-of-thought (CoT) reasoning, improves performance on downstream tasks (Fan et al., 2024; Nguyen et al., 2025; Abdin et al., 2024) and training token efficiency (Kimi Team et al., 2025). These pipelines often incorporate a stage that reformats raw answers into CoT reasoning traces, encouraging systematic reasoning. Within this line of work, Fan et al. introduces Reformatted Alignment (ReAlign), a format-driven pipeline that upgrades instruction datasets through three stages: (i) hu-

mans define CoT formats; (ii) enrichment adds auxiliary information; and (iii) reformatting imposes an explicit CoT structure.

Despite *SecKnowledge*'s breadth, responses tend to be concise with short rationales. A pipeline such as ReAlign can expand these compact answers into explicit, step-by-step trajectories while grounding them in retrieved documents and authoritative sources, making it a natural baseline and a strong foundation for *SecKnowledge 2.0*. At the same time, instruction generation in complex domains is prone to hallucinations (Jiang et al., 2023) and divergence from expert intent (Levi et al., 2025; Ramjee et al., 2025; Eachempati et al., 2025). We therefore believe a more domain-appropriate pipeline for cybersecurity should be adopted.

3.3 Pipeline Extensions

In the next section, we move beyond vanilla reformatting by introducing an expert-in-the-loop workflow that semi-automatically derives domain-specific formats for each task in the dataset. These formats specify the exact reasoning steps needed to reach the final answer. We further enhance them with document grounding and targeted web search, ensuring that each step is anchored in evidence and minimizing hallucinations during reformatting.

3.3.1 Expert-in-the-Loop System for Automating Domain-Specific Formats

For reformatting and enriching a given dataset D, the first step is to partition it into distinct tasks $\{T_1, ..., T_N\}$, each task representing a coherent sub-domain or capability. Formally: $S = \{T_1, ..., T_N | \bigcup_{k=1}^{k=N} T_k = D, T_i \cap T_j = \varnothing\}$. Since different problem types demand different ways of structuring outputs, each task $\mathbf{T_i}$ must be paired with a corresponding format $\mathbf{F_i}$ (refer to Figure 7 for an example format) that defines the task more precisely by specifying the steps needed to be taken to provide a detailed and logically coherent answer. Manually constructing such tailored formats, however, can be highly time-consuming, particularly in specialized domains such as cybersecurity, where expert knowledge is required, yet remains both scarce and costly.

To efficiently scale format definition across a large and hierarchical label space - such as SecKnowledge, which contains 105 unique tasks - we developed an expert-in-the-loop system capable of semi-automatically generating and evaluating format templates. The system employs a LLM that, given a concise task description together with an optional set of illustrative instruction–response examples from any task, generates a corresponding candidate output format. Within the same framework, experts can immediately evaluate this format by executing the full pipeline on representative inputs, obtaining rewritten responses along with auxiliary feedback such as search results and LLM-as-a-judge scores for readability and factuality. Based on this feedback, experts can directly edit the format and rerun the pipeline, enabling a tight feedback loop that supports iterative refinement while substantially reducing the manual burden of format specification and enhancing the efficiency, accuracy, and scalability of the pipeline. For implementation details, refer to Appendix A.1.

3.3.2 LLM-Guided Search and Document Grounding Pipelines

The vast majority of tasks in SecKnowledge can greatly benefit from enrichment through evidence retrieval. Such grounding is necessary to reduce the risk of LLM hallucinations when rewriting responses and to ensure that outputs remain accurate and reliable. Evidence can be provided in two primary ways: (1) by attaching a grounding document directly to the instruction–response pair, such as an advanced persistent threat (APT) report describing a specific attack, or (2) by searching for relevant documents on demand. The first method is largely straightforward, as it simply links an instruction–response pair to the document from which it was derived. The second method, however, requires more substantive mechanisms, such as searching a pre-indexed corpus (e.g., via a vector database) or the world wide web. Accordingly, the discussion that follows concentrates on the latter, given its broader applicability and scalability. To obtain high-quality search results, we design the mechanism as a structured multi-step process:

1. **Query building.** Given only the instruction, the LLM is prompted to generate K candidate search queries. This stage can be viewed as a brainstorming step to provide diverse queries.

2. **Query filtering.** A second LLM, conditioned on the instruction, the original answer, the task format, and the candidate queries, selects only those queries expected to provide new or useful information that can fill gaps.

3. **Results retrieval.** The filtered queries are then executed against either a vector database or the web, with the top R_{max} results retrieved for each query (yielding $\leq K \times R_{max}$ results).

4. **Results parsing.** For each query, the top R results that could be parsed to text are retained, while un-processable ones (e.g., websites that block automated access) are discarded.

5. **Optional summarization.** When retrieved documents are large (e.g., web pages), they may be summarized in a manner conditioned on the task format, ensuring that the retained content aligns with the information required to populate the format steps.

In our experiments, we used $K = 2$, $R_{max} = 8$, and $R = 2$, without applying summarization. This configuration is motivated by two considerations: (1) automatic summarization often omits critical details required by the task format, and (2) full documents, when not summarized, can accumulate into a large number of tokens that risk exceeding the context window allocated for the LLM. Moreover, even when the context window is not exceeded, long inputs can lead the model to disproportionately attend to the beginning and end of the prompt rather than its middle content (Liu et al., 2023), effectively nullifying the benefit of providing additional context. To balance these constraints, we restricted retrieval to at most four results ($K \times R = 4$), thereby prioritizing fewer, higher-quality search results over larger volumes of noisier content.

Instruction
What are the required skills to execute the attack pattern: Leveraging Active Adversary in the Middle Attacks to Bypass Same Origin Policy (CAPEC ID: 466)

SecKnowledge Answer
The skills required to execute Leveraging Active Adversary in the Middle Attacks to Bypass Same Origin Policy (CAPEC ID: 466) are the following:
1. Ability to intercept and modify requests / responses The level of the required skills can be classified as Low.
2. Ability to create iFrame and JavaScript code that would initiate unauthorized requests to sensitive sites from the victim's browser The level of the required skills can be classified as Medium.
3. Solid understanding of the HTTP protocol The level of the required skills can be classified as Medium

SecKnowledge 2.0 Answer

1. Attack Pattern Overview
CAPEC-466 – Leveraging Active Adversary in the Middle Attacks to Bypass Same Origin Policy
This pattern describes how an attacker positioned as a man-in-the-middle (e.g., on a public Wi-Fi) injects an invisible iFrame into an unencrypted HTTP response. The iFrame forces the victim's browser to issue automatic requests to a privileged domain, which the attacker then intercepts, redirects, and enriches with malicious JavaScript. By exploiting the Same Origin Policy, the attacker can steal cookies (including HTTP-only), credentials, and other sensitive data from any site they choose.

2. Technical Mechanics Involved
- Interception and modification of HTTP requests/responses on an unsecured network.
- Injection of iFrames that trigger cross-origin requests from the victim's browser.
- Real-time redirection of those automatic requests back to attacker-controlled services.
- Injection of malicious JavaScript into the responses of the targeted privileged site, allowing code execution under that site's origin.
- Exploitation of persistent and session cookies without needing XSS-style vulnerabilities.

3. Core Skills Required

Skill	Definition & Relevance	Difficulty to Master	Impact on Attack Effectiveness
Intercept & modify HTTP traffic	Ability to capture, read, and alter HTTP requests and responses flowing between the victim and web servers (e.g., using proxy tools or packet sniffers). This is essential for inserting the malicious iFrame and for redirecting the victim's automatic requests.	**Low** – Basic networking tools (Wireshark, mitmproxy) suffice; no deep programming needed.	Enables the initial foothold; without it the attacker cannot inject the iFrame or reroute traffic, making the attack impossible.
Create iFrames and craft JavaScript for unauthorized cross-origin requests	Skill in writing HTML iFrames and JavaScript that silently cause the browser to send requests to a target domain, then capture or manipulate the responses. This drives the victim's browser to interact with the privileged site under the attacker's control.	**Medium** – Requires familiarity with client-side scripting, DOM manipulation, and browser security models.	Determines how stealthy and reliable the request redirection is; well-crafted scripts reduce detection and increase success rates.
Solid understanding of the HTTP protocol	Comprehensive knowledge of HTTP methods, headers, cookies, and the mechanics of request/response cycles. Critical for correctly modifying traffic, preserving session cookies, and ensuring the injected content is accepted by the browser and server.	**Medium** – Involves grasping protocol nuances, status codes, and security headers.	Directly affects the precision of traffic manipulation; errors can break the session or alert the victim, lowering attack reliability.

4. Conclusion
Executing CAPEC-466 hinges on three primary capabilities: low-level traffic interception, intermediate client-side scripting to embed malicious iFrames, and a solid grasp of HTTP fundamentals. While the interception skill is relatively easy to acquire, the scripting and protocol expertise are moderately demanding but crucial for maintaining stealth and ensuring the attack's effectiveness. Mastery of these areas enables an adversary to bypass Same Origin Policy protections and harvest sensitive data from targeted sites.

Figure 3: Q&A example from SecKnowledge (green), and our improved answer (orange).

4 Training and Evaluation Process

We detail the training and evaluation pipelines. For the evaluation, we report results on widely used open-source security benchmarks. When comparing to state-of-the-art frontier models (such as Sec-Gemini v1), we follow the evaluation protocol of Sec-Gemini v1 and report results on the well-known CTIBench-RCM and CTIBench-MCQ (Alam et al., 2024). Additionally, for both the baseline and our fine-tuned models, we evaluate on further benchmarks (Li et al., 2023; Tihanyi et al., 2024; Levi et al., 2025), as elaborated in Section 4.2.

4.1 TRAINING RECIPE

To train our models, we use our generated *SecKnowledge 2.0* dataset. We employ Qwen3-4B-base, Qwen3-8B-base, and Qwen3-14B-base, alongside gpt-oss-20b as our starting point. Training is performed with a learning rate of 4×10^{-5} and a linear warm-up ratio of 0.15. The context length is set to 8192, and the batch size is 3072. We train our models for two epochs.

To train our models with adaptive reasoning capabilities, we incorporate adaptable reasoning depth: long-form chain-of-thought examples from SecKnowledge 2.0 are augmented with "step-by-step" requests, while shorter instructions from the original SecKnowledge dataset are paired with concise, fast-response requests. This design, similar to the notion of reasoning effort in gpt-oss, balances reasoning-intensive and lightweight tasks. For the shorter, fast-response requests, we sample approximately 25% of the original instructions and responses from the original SecKnowledge dataset, focusing primarily on short, high-quality examples selected using LLMaaJ. The procedure of mixing a portion of the high-quality original responses with their enhanced counterparts not only teaches the models to perform adaptive reasoning, but also improves token utility by amplifying the volume of high-quality tokens while reducing overfitting, as observed by Kimi Team et al. (2025).

Additionally, we observed a phenomenon also reported in recent studies (Huerta-Enochian & Ko, 2024; Shi et al., 2024; Chatterjee et al., 2025): it is often preferable to retain at least partial loss on the prompt rather than masking it out entirely during training. Finally, we conducted experiments to determine whether a base or a post-trained model is a better starting point for fine-tuning. We found that base models tend to learn more effectively than their post-trained counterparts. Appendix B presents additional training details, alongside a small-scale experiment comparing Qwen3-8B and Qwen3-8B-post-trained under the same training recipe, illustrating the differences between starting from a base versus a post-trained model.

4.2 EVALUATION BENCHMARKS

We evaluate models exclusively on cybersecurity benchmarks spanning governance/compliance, architecture/operations, and threat detection & response. The suite emphasizes document-grounded reasoning, consistent mapping across security taxonomies, and resilience to adversarial distractors. Our evaluation uses the benchmarks listed below; See Appendix C.1 for further details and statistics.

CTI-MCQ tests breadth of CTI knowledge via multiple-choice items on attack patterns, actors, detections, mitigations, and frameworks (Alam et al., 2024). **CTI-RCM** evaluates document-grounded root-cause mapping by linking CVE evidence and bug reports to the correct CWE(s) with taxonomy-aware disambiguation (Alam et al., 2024). **SecEval** offers over 2,000 multi-option questions across nine security domains from authoritative sources, measuring accurate recall and the ability to apply controls and frameworks to concrete scenarios (Li et al., 2023). **CyberMetric-2000** comprises 2000 expert-validated questions spanning diverse subdomains, indicating professional-level declarative security knowledge under closed-book conditions (Tihanyi et al., 2024). **CISSP exams** contains questions drawn from the assessment tests within the CISSP learning material, assessing analysts' skills across the entire security posture. **Technical Weakness Impact Mapping** requires assigning CWE descriptions a weakness to one or more of eight technical impacts, emphasizing consequence-centric reasoning beyond exploitability (Levi et al., 2025). **Adversarial CTI** ties questions to specific MITRE ATT&CK entities and uses adversarial distractors to probe robustness on campaigns, tactics, detections, and mitigations (Levi et al., 2025). **CTI Detection & Mitigation** checks whether models propose appropriate detections and mitigations for tactics/techniques, attack patterns, weaknesses, and vulnerabilities (Levi et al., 2025). **CTI Relationship Prediction** tests cross-taxonomy reasoning and relationship *hallucinations* by choosing the correct justification for whether two CTI entities (e.g., CVE and CWE mapping) are related (Levi et al., 2025).

Figure 4 shows the benchmark's distribution across our cybersecurity taxonomy — domain-specific categories used to quantify coverage across the cybersecurity landscape (see Appendix C.2.1). Our benchmarks are closely aligned with organizational security priorities, with a particular focus on *threat Intelligence*, *incident response*, *security operations*, *application security*, and *identity management*. This alignment ensures that evaluation outcomes are not only theoretically sound but also operationally relevant to real-world defensive strategies.

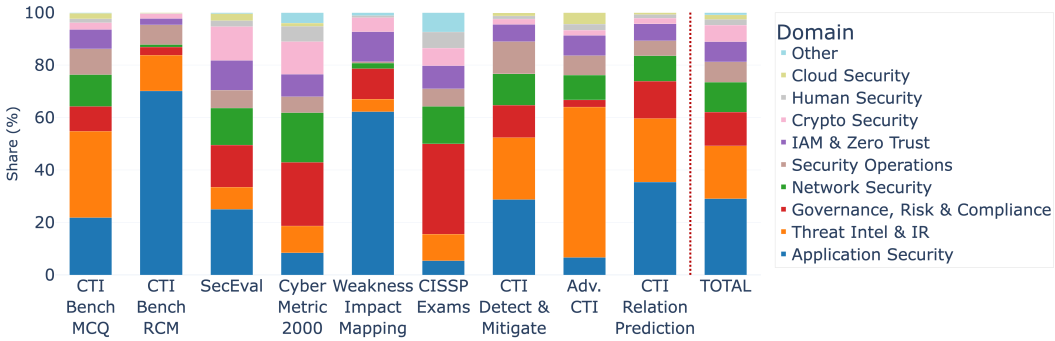


Figure 4: Domain composition of each data source in the evaluation benchmarks.

4.3 Evaluation Process and Metrics

Similar to Wang et al. (2024), we also found that models utilizing Chain of Thought (CoT) reasoning achieved better performance on complex security benchmarks, compared to direct answering. Therefore, we utilize a zero-shot CoT prompting. The CoT template incorporates essential reasoning steps and format to allow models to easily follow the given instructions. We used zero-temperature for consistency. We then use a regular expression parser to extract the final answer from the model's CoT process. The prompt used in the evaluation is provided in Figure 11 in Appendix D. For the Qwen suite of models, we compared our fine-tuned versions to baseline models (post-trained) with the *thinking* flag enabled, allowing them to leverage their reasoning process. For gpt-oss, we used reasoning effort *Medium* to avoid failures caused by the full CoT exceeding maximum window size.

5 CyberPal 2.0: A Suite of Cybersecurity Language Models

To demonstrate the effectiveness of our method, we train a family of security-expert SLMs ranging from 4B to 20B parameters. We then report results against the post-trained versions of the same base models from which our models were fine-tuned, alongside results against state-of-the-art frontier models (e.g., o1, Sec-Gemini v1). Lastly, we perform ablation studies.

5.1 Results

Results Compared to Baselines. In Table 1, we present results compared to the baseline models from the same families that CyberPal 2.0 was fine-tuned from. Meaning, for example, we measure improvements across various benchmarks between Qwen3-8B and CyberPal 2.0-8B, which was fine-tuned from Qwen3-8B-base. Similarly, we compare the other models. On average, our models outperform their baselines by 7–14%. We also observe substantial gains on key benchmarks such as CTIBench-RCM, where our models exceed the baselines by 16–31%, and CTIBench-MCQ, where they achieve improvements of 8–12%. We also include gpt-oss-120B as a reference to highlight our models' strong performance.

Results Compared to Open Source cybersecurity models. We further evaluated our models against recent 7B–8B open-source cybersecurity models. We adopt the evaluation protocol from Section 4.3 and assess recent open-source cybersecurity models Weerawardhena et al. (2025); Yu et al. (2025); SegoLily Labs; DeepHat-V1. We omit PRIMUS-Reasoning on CTIBench because its training set was distilled from CTIBench Yu et al. (2025), making the comparison unfair. Since the baselines are 7B–8B, we report our 8B variant for a like-for-like comparison. Table 2 presents the full results: our 8B model outperforms all open-source baselines by a substantial margin.

Results Compared to Frontier LLMs. Finally, we evaluated our models against state-of-the-art general models such as Sec-Gemini v1 and OpenAI's o1. As evaluation is costly, we follow Sec-Gemini v1 evaluation protocol and report results on the CTIBench benchmarks: CTIBench-MCQ and CTIBench-RCM (Alam et al., 2024). CTIBench-MCQ assesses an LLM's understanding of core cyber–threat intelligence concepts, while CTIBench-RCM evaluates model's ability to perform

Table 1: Evaluation results for CyberPal 2.0 models compared to their corresponding baseline (post-trained) models and the gpt-oss-120B open-source model.

Model	CTI Bench MCQ	CTI Bench RCM	SecEval	Cyber Metric 2000	CISSP Exams	Adv. CTI	Weakness Impact Mapping	CTI Detect & Mitigate	CTI Relationship Prediction	Avg.
Qwen3-4B	61.88	49.95	57.38	87.40	79.80	64.51	57.02	60.77	67.99	65.19
CyberPal-2.0-4B	**69.70 (+7.82)**	**81.15 (+31.20)**	**59.02 (+1.64)**	**87.80 (+0.40)**	**80.80 (+1.00)**	**68.03 (+3.52)**	**66.48 (+9.46)**	**64.03 (+3.26)**	**77.12 (+9.13)**	**72.68 (+7.49)**
Qwen3-8B	63.13	63.25	56.19	88.45	83.33	64.93	53.58	59.88	60.67	65.93
CyberPal-2.0-8B	**75.15 (+12.02)**	**85.95 (+22.70)**	**66.93 (+10.74)**	**89.85 (+1.40)**	**88.89 (+5.56)**	**87.61 (+22.68)**	**71.06 (+17.48)**	**70.26 (+10.38)**	**87.66 (+26.99)**	**80.37 (+14.44)**
Qwen3-14B	64.28	70.50	61.48	89.85	86.36	69.43	62.46	63.44	58.48	69.59
CyberPal-2.0-14B	**75.51 (+11.23)**	**86.00 (+15.50)**	**69.71 (+8.23)**	**89.95 (+0.10)**	**90.40 (+4.04)**	**89.58 (+20.15)**	**70.77 (+8.31)**	**70.95 (+7.51)**	**92.93 (+34.45)**	**81.76 (+12.17)**
gpt-oss-20B	64.57	68.95	67.65	**90.20**	79.80	61.83	**71.91**	67.49	65.42	70.87
CyberPal-2.0-20B	**75.71 (+11.14)**	**87.40 (+18.45)**	**72.86 (+5.21)**	89.05	**86.87 (+7.07)**	**84.93 (+23.10)**	70.77	**67.69 (+0.20)**	**87.66 (+22.24)**	**80.33 (+9.46)**
gpt-oss-120B	69.37	79.95	68.02	92.55	84.34	72.76	65.90	64.52	70.56	74.21

Table 2: Evaluation results for CyberPal 2.0 8B compared to the recent opens-source cyber security models. (*) Primus-reasoning average is missing CTI benchmarks because its training set was distilled from CTIBench

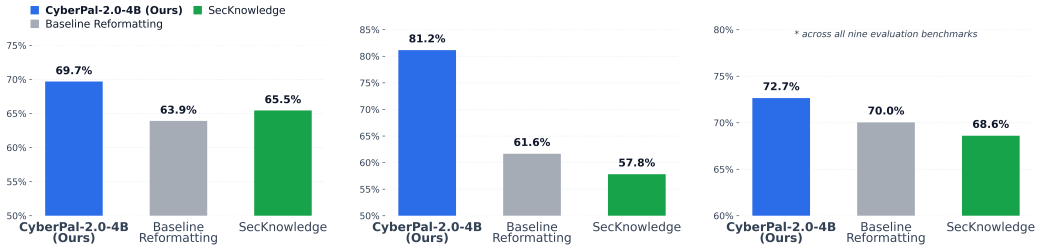
Model	CTI Bench MCQ	CTI Bench RCM	SecEval	Cyber Metric 2000	CISSP Exams	Adv. CTI	Weakness Impact Mapping	CTI Detect & Mitigate	CTI Relationship Prediction	Avg.
DeepHat-v1-7B	61.24	68.1	33.21	84.0	76.76	63.23	60.74	56.12	52.05	61.72
Lily-Cybersecurity-7B-v0.2	55.31	42.9	37.14	80.0	68.18	58.45	52.43	39.71	46.34	53.38
Primus-merged	65.2	63.9	59.06	85.1	78.28	64.92	55.3	50.77	59.98	64.72
Primus-reasoniong	-	-	53.03	86.05	73.23	64.78	53.58	52.24	58.79	63.01(*)
Foundation-Sec-8B-Instruct	63.24	67.95	54.81	84.5	69.69	68.87	60.74	55.52	57.31	64.74
CyberPal-2.0-8B	**75.15**	**85.95**	**66.93**	**89.85**	**88.89**	**87.61**	**71.06**	**70.26**	**87.66**	**80.37**

Root Cause Mapping (RCM), identifying the underlying causes of vulnerabilities by correlating vulnerabilities records and bug tickets with weaknesses. This benchmark is considered a leading threat intelligence benchmark and serves as a strong indicator of a model's threat management capabilities.

As shown in Figure 1, our models are on par with—or better than—most frontier models. **RCM:** CyberPal 2.0–20B ranks first overall, surpassing Sec-Gemini v1; the 14B, 8B, and 4B variants all ranked second and exceed the remaining frontier models. **MCQ:** the 20B and 14B models ranks second and third respectively, immediately behind Sec-Gemini v1 and ahead of o1; the 8B model is competitive with GPT-4o; and even the 4B model outperforms much larger models such as Mistral Large and DeepSeek-v3, with performance close to o3-mini.

5.2 Ablation Studies and LLM-as-a-Judge Evaluation

We conduct ablation studies to verify that the observed gains are attributable to our contributions. First, we measure the impact of *data quality* by training on the original SecKnowledge versus our improved dataset. We refer to this model as *SecKnowledge*. Second, we isolate the effect of our improved reformatting and enrichment pipeline, which extends the reformatting pipeline suggested in Fan et al. (2024). We use the pipeline of Fan et al. (2024) to improve the orignal SecKnowledge, refer to this model as *Baseline Reformatting*. All ablations are run on the same base model (Qwen3-4B-base) under an equal training budget (two epochs) and identical optimization and context settings (§4.1), and are evaluated on all nine evaluation benchmarks.



(a) CTIBench MCQ (b) CTIBench RCM (c) Avg. across all benchmarks

Figure 5: Ablation studies (using 4B parameters models) comparing *CyberPal 2.0-4B (Ours)* against *Baseline Reformatting* (Fan et al., 2024) and *SecKnowledge* (Levi et al., 2025).

In Figure 5, we visualize results for CTIBench-MCQ and CTIBench-RCM (§4.2), as well as the average improvement over all nine benchmarks. Full results for all benchmarks are presented in Table 6 in Appendix E. As shown in Figure 5, our model consistently outperforms both the original SecKnowledge-based model and the Baseline Reformatting-based model.

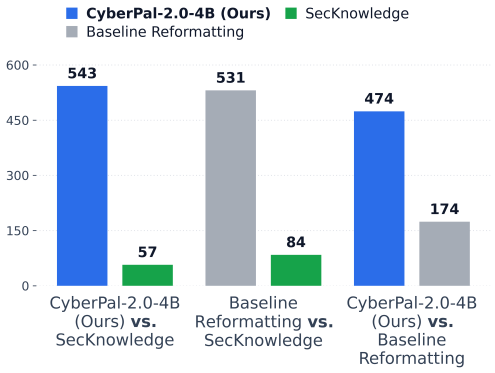


Figure 6: Pairwise comparison results from LLMaaJ (OpenAI's o3) with expert provided *grounding*.

Finally, we assess answer quality via *LLM-as-a-Judge* (LLMaaJ) (Zheng et al., 2023). 30 cybersecurity experts authored 115 open-ended questions spanning command-line risk assessment, enterprise security, general cybersecurity, network security, and CTI-related topics. We used OpenAI's o3 as the judge. For each question and pair of model answers, the judge received expert-curated grounding documents. To validate the judge, we measured agreement with human experts and found that, with proper grounding, o3 aligns with human preferences in over 90% of cases. As seen in Figure 6, our model is consistently preferred over both baselines. See Appendix F for experiment details and additional results.

6 Conclusion

CyberPal 2.0 demonstrates that compact, domain-specific SLMs (4B–20B) can deliver frontier-level capability for security operations without frontier-level cost. Built on *SecKnowledge 2.0*—with schema-driven reformatting, expert-in-the-loop enrichment, and a multi-step grounding process—our models achieve 7–14% average gains over strong open-source baselines and, on core CTI tasks, match or surpass leading closed models; notably, the 20B model outperforms GPT-4o, o1, o3-mini, and Sec-Gemini v1, while even the 4B variant ranks second. Ablations and LLMaaJ validated by human experts attribute the gains primarily to data-quality improvements from our **SecKnowledge 2.0** enhanced reformatting and enrichment pipeline.

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A PIPELINE EXTENSIONS DETAILS

A.1 FORMAT GENERATION FRAMEWORK

The system is composed of three primary stages, with the second and third stages forming an iterative loop that can be repeated until the user is satisfied with the resulting format, as illustrated in Figure 8. It is important to note that this framework is applicable only once the set of tasks covering the entire dataset has been defined, at which point the process is limited to the generation of formats.

Data Exploration & Example Selection. First, the user selects the appropriate category and task from the menus. From N available examples for each task ($N = 500$ in our case), the system samples k instruction–answer pairs for inspection ($k = 1$ in Fig. 8). This stage enables the user to explore the dataset - examining the range of questions and corresponding answers for the selected task - and to identify representative examples. These examples are subsequently used both to guide format generation and as inputs to the pipeline.

Format Generation. Second, the user provides a brief description of the task, this description will be used both to classify unlabeled instructions from the dataset and to generate the format. Then he selects an LLM to produce a candidate format using one of the available prompts. In our case, two distinct prompts were required: one tailored for specific tasks - such as the instructions generated in the first stage of *SecKnowledge*, which originate from a defined source and consistently ask for the same type of information, albeit in different contexts - and another designed for more general tasks, which encompass a wide variety of instructions, as in the second stage of *SecKnowledge*. In the latter case, providing examples may bias the format toward the selected instances, which is undesirable. The framework further supports the seamless addition of new prompts if needed. Once generated, the format can be refined by the user through manual editing.

Evaluation Through Pipeline Execution. Third, the user can run the pipeline on any example, with the first example automatically pre-filled by default. During this step, the user may adjust various hyper-parameters - for instance, enabling or disabling web search, specifying the number of search queries and the number of results per query, and deciding whether to summarize each retrieved before including it in the rewriting context. A grounding document can also be provided, either as an alternative to or in addition to web search. The pipeline then outputs the rewritten response, quality assessment scores, and, if requested, the retrieved search results.

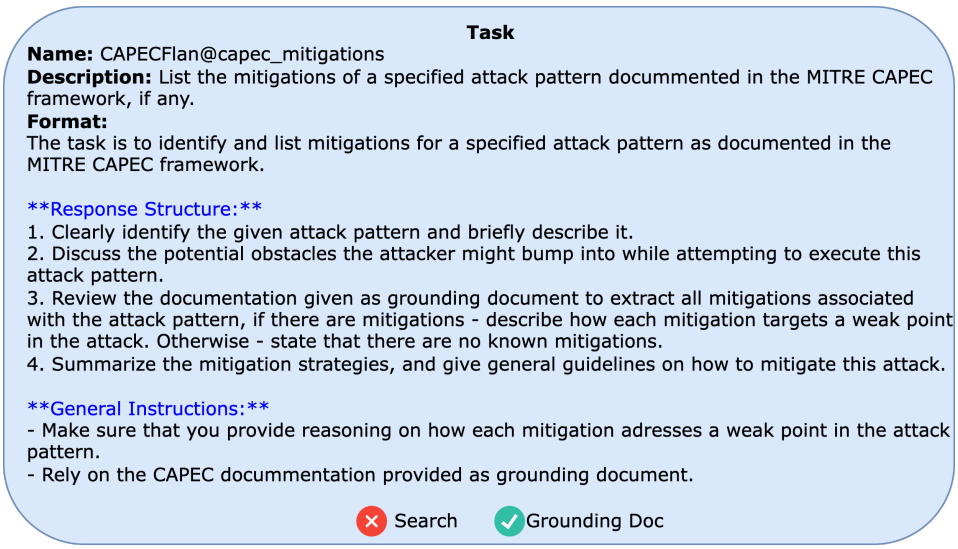

Figure 7: An example task, specifically the one illustrated in Figure 3. A task consists of a name, a description, a format, whether it requires search, and whether it requires a grounding document.

[2]https://www.gradio.app/

A.2 Data Generation Quality Assessment

After rewriting the original answer according to the format, the pipeline also incorporates evaluation in the form of LLM as a Judge. There are 2 criteria by which we judge the answers generated by the pipeline.

1. **Readability.** We prompt the judge with the instruction, and both answers and ask it to select the better answer according to the criteria described in Figure 12 (original and rewritten). We do this two times - in the first time the original answer is first and the rewritten is second, and in the second time the order is the opposite (while anonymizing which one is the original one and which one is the rewritten one). We test both directions to avoid positional bias (Wang et al., 2023; Zheng et al., 2023).
2. **Factuality.** We prompt the judge with the original answer and the rewritten answer, emphasizing that the original answer is the ground truth, and ask the LLM to provide a score in a scale of 1-10 that determines how factual the rewritten answer with respect to the original answer.

By combining these two criteria, we can get a sense of the quality of the defined formats and the new dataset. In Figure 9, we present the quality assessment results on our dataset, *SecKnowledge 2.0*. On average, the new answers are preferred 85.62% of the time (with 5.55% to the favor of the original answers, and 8.56% of inconsistency, where switching the position of the answers changed the judge decision, the rest are ties), while maintaining the factuality, reflected by an average factuality score of 9.25. These results show that our pipeline is robust.

B Training Recipe Additional Details

Training from base vs. post-trained model. In Table 3, we present a small-scale experiment examining the effect of the starting checkpoint *using an identical training recipe and evaluation protocol*. Using Qwen3-8B, we evaluate how fine-tuning with *SecKnowledge 2.0* affects performance when starting from the base model versus a post-trained model. We observed an interesting phenomenon: directly fine-tuning the base model (i.e., Qwen3-8B-Base) yields significantly better results than relying on the post-trained model (Qwen3-8B) as the starting point. This effect is amplified on benchmarks that require additional reasoning to arrive at the final answer (e.g., CTIBench-RCM). On average, fine-tuning from the base model provides a 15.16% improvement across the key benchmarks, whereas starting from the post-trained model provides a 5.62% improvement relative to the Qwen3-8B baseline—corresponding to a $2.7\times$ larger gain when initializing from the base model. For open-ended benchmarks such as CTIBench-RCM, the difference is even more pronounced: the model fine-tuned from the base checkpoint achieves a 22.7% improvement, compared with 1.85% for the model fine-tuned from the post-trained checkpoint. Although limited in scope, this experiment empirically indicates that, given sufficiently high data quality, initializing from a base model enables more effective learning than starting from a post-trained checkpoint that has already undergone extensive supervised fine-tuning and alignment–yet further work is needed to systematically disentangle how data quality and data scale interact with the choice of starting checkpoint during fine-tuning.

Table 3: Comparing the improvement of fine-tuning our models when starting from base model vs. a post-trained model.

Model	CTIBench MCQ	CTIBench RCM	SecEval	Avg.
Qwen 3 8b	63.13	63.25	56.19	60.85
CyberPal2.0-8B (trained from Qwen3-8B)	68.90	65.10	65.42	66.47
CyberPal2.0-8B (trained from Qwen3-8B-Base)	**75.15**	**85.95**	**66.93**	**76.01**

Incremental training methodology. Lastly, consistent with the observations of Mitra et al. (2023); Levi et al. (2025), we empirically find that exposing the model to instructions of progressively in-

creasing length—often correlated with task difficulty—enhances its learning capacity. Building on this principle, we adopt an incremental training methodology organized at the dataset level. Specifically, we first present the model with instructions from the original SecKnowledge dataset, followed by instructions from our new SecKnowledge 2.0 dataset.

Additional training details. We select the final checkpoint by validation loss on a held-out split extracted from the training set. We train for two epochs, as we observe diminishing returns and an increased risk of overfitting thereafter. Training was conducted on a cluster of 12 NVIDIA A100 80 GB GPU nodes, and evaluation was performed on NVIDIA H100 80GB GPUs.

C Evaluation benchmarks, statistics, and analysis

C.1 Evaluation benchmarks

CTI-MCQ (Alam et al., 2024) is a multiple choice question benchmark aimed at assessing LLMs' capabilities in understanding crucial cyber threat intelligence concepts including attack patterns, threat actors, APT campaigns, detection methods, mitigation strategies, common software vulnerabilities, attack pattern enumeration, alongside public CTI quizzes. This benchmark assess the breadth of CTI/domain knowledge; knowing frameworks/controls and when to apply them.

CTI-RCM CTI Root Cause Mapping (RCM) (Alam et al., 2024) identifies the underlying weakness(es) of a vulnerability by correlating CVE records and related bug tickets with CWE entries. Accurate root cause mapping is essential for guiding investments, policies, and practices aimed at addressing and eliminating these vulnerabilities. Strong LLM performance on CTI-RCM indicates grounded, document-linked reasoning and consistent, taxonomy-aware disambiguation—mapping real-world vulnerability evidence to the appropriate CWE(s) rather than relying on superficial keyword matches.

SecEval SecEval (Li et al., 2023) is a multiple-choice, multiple-option benchmark for evaluating LLMs' cybersecurity knowledge, with over 2,000 questions spanning nine domains. SecEval was constructed using OpenAI GPT-4 from authoritative sources (open-licensed textbooks, official platform security docs, OWASP guides, CWE, and MITRE ATT&CK/D3fend). This benchmark assesses the breadth and accuracy of security/domain knowledge and the ability to choose and apply the right frameworks, controls, detections, and mitigation to concrete scenarios.

CyberMetric 2000 CyberMetric (Tihanyi et al., 2024) is a benchmark dataset for evaluating LLMs' knowledge in cybersecurity. The questions for the benchmark were created through a collaborative process, i.e., merging expert knowledge with LLMs. We used the 2000 questions dataset, verified by human evaluators, which covers a wide range of topics within cyber-security, validated by security experts. As questions come from standards-grounded material and were validated by certified practitioners (e.g., CISSP/CISM/OSCP), strong performance primarily evidences professional-level declarative cybersecurity knowledge—accurate recall of definitions, controls, and best practices across diverse subdomains, and the ability to reject plausible distractors under closed-book conditions.

CISSP Exams Introduced by Levi et al. (2025), this benchmark uses exam-style questions from CISSP preparation materials to assess broad, professional cybersecurity knowledge across governance and risk, security architecture, operations, software and network security, and identity and access management. Items use plausible distractors and test principled reasoning and terminology rather than tool-specific tricks. A high score indicates strong declarative understanding, standards-aligned judgment, and the ability to separate best practices from common misconceptions under test conditions.

Technical Weakness Impact Mapping In CWE, each weakness, if successfully exploited, can lead to one or more technical impacts out of eight options: modify data, read data, DoS: unreliable execution, DoS: resource consumption, execute unauthorized code or commands, gain privileges / assume identity, bypass protection mechanism, and hide activities. This evaluation benchmark, introduced by Levi et al. (2025), presents the model with CWEs and their descriptions, where the goal is to map each CWE to its related technical impact. A high score indicates taxonomy-aware understanding of how specific weakness patterns translate into concrete consequences, beyond surface keyword matching. Because a single CWE can map to multiple impacts and descriptions are often terse,

the benchmark primarily measures consequence reasoning rather than exploit feasibility or business risk. It thus serves as an impact-from-weakness signal that complements severity or exploitability evaluations.

Adversarial CTI Levi et al. (2025) compiled an adversarial evaluation dataset from various MITRE ATT&CK sources to evaluate models on malicious software, campaigns, tactics, and corresponding detections and mitigations. Each input provides a question related to a specific MITRE instance, with the correct label being its corresponding source. To further challenge the models and test robustness, they introduced a novel adversarial attack for multiple-choice questions, where the attack chooses the false options that will confuse the model with the highest probability.

CTI Detection and Mitigation Introduced by Levi et al. (2025), this benchmark is designed to assess a model's ability to provide appropriate detections and mitigations for different attack tactics and techniques, attack patterns, weaknesses, and vulnerabilities.

CTI Relationship Prediction A major role of cyber threat management expert model is to comprehend the relationships between different CTI frameworks. This dataset (Levi et al., 2025) evaluates the ability to differentiate between false and correct relationships among CTI entities. For example, it presents the model with two entities (e.g., instances of CVE and CWE) and two possible explanations—one justifying why the entities are related and another explaining why they are not. The objective is for the model to reason and determine which explanation is correct.

C.2 Evaluation statistics analysis

In this section, we provide details about the statistics and domain coverage of the security evaluation benchmarks. To evaluate the applicability of LLMs in cybersecurity, we first structured our evaluation set around domain-specific categories. The objective was to establish whether tasks align with areas such as threat intelligence, security operations, or identity and application security, and to provide a principled basis for mapping questions to specific domains of cybersecurity. A taxonomy-driven approach enables both standardized evaluation and benchmarking of model performance in a manner consistent with industrial and academic practices.

As part of this process, we explicitly built upon and extended two taxonomies: taxonomy of cybersecurity domains Weerawardhena et al. (2025) and the SecEval benchmark dataset for security evaluation Li et al. (2023). By synthesizing insights from both Weerawardhena et al. industrial perspective and SecEval's categorization, we constructed a unified taxonomy that captures enterprise security concerns while remaining aligned with established evaluation standards.

Our benchmarks are closely aligned with organizational security priorities, with a particular focus on *threat Intelligence*, *incident response*, *security operations*, *application security*, and *identity management*. This alignment ensures that evaluation outcomes are not only theoretically sound but also operationally relevant to real-world defensive strategies.

Through this integration, we ensured that our taxonomy is both conceptually rigorous and operationally validated, bridging the gap between industrial practice and academic research in cybersecurity evaluation.

C.2.1 Cybersecurity Categories

We defined the following ten high-level categories, each with a set of sub-categories capturing specific security concerns:

1. **GCR (Governance, Risk, and Compliance)**
   - Risk Management & Security Strategy
   - Compliance and Regulations (e.g., GDPR, HIPAA)
   - Security Frameworks (e.g., NIST CSF, ISO 27001)
   - Security Policies & Architecture
2. **NetSec (Network, Infrastructure, and Endpoint Security)**
   - Perimeter and Network Security (Firewalls, VPNs, Wireless)
   - Endpoint Protection & MDM

- IoT and OT/ICS Security
- Mobile Security

3. **AppSec (Application and Software Security)**
   - Secure Software Development (DevSecOps)
   - Application & API Security
   - Vulnerability Management & Penetration Testing
   - Software Supply Chain Security (SBOM, third-party risk)
4. **CloudSec (Cloud and Data Security)**
   - Cloud Security Architecture & Tools
   - Identity and Access Management (IAM, PAM)
   - Data Loss Prevention & Privacy (DLP, encryption)
   - Cloud Compliance & Shared Responsibility Model
5. **IAM_ZT (Identity, Access, and Zero Trust)**
   - Authentication & Authorization (MFA, SSO, RBAC)
   - Identity Governance & Lifecycle
   - Zero Trust Architecture
   - Privileged Access Controls
6. **SecOps (Security Operations and Monitoring)**
   - SIEM, SOC, and Log Management
   - Security Automation & SOAR
   - Detection Engineering
   - Operational Resilience & Monitoring
7. **ThreatOps_IR (Threat Intelligence and Incident Response)**
   - Threat Detection, Analysis & Hunting
   - Threat Intelligence Platforms & IOCs
   - Advanced Persistent Threats (APTs)
   - Malware Techniques
   - Incident Response, Recovery & Digital Forensics
8. **CryptoSec (Cryptography and Secure Communications)**
   - Cryptographic Algorithms & PKI
   - Key Management
   - Post-Quantum Cryptography
   - Secure Protocols and Encryption Practices
9. **HumanSec (Security Awareness and Human Risk)**
   - Social Engineering Techniques (Phishing, Pretexting)
   - Insider Threat Management
   - Security Awareness Training
   - Behavioral Risk Analysis
10. **Other**
    - Cross-domain or emerging categories not covered above.

This taxonomy provided a structured basis for categorizing data and aligning evaluation with both research benchmarks and enterprise needs.

C.2.2 MULTI-LABEL CLASSIFICATION

To carry out the mapping, we employed a large open-source language model (OSS-120B), which was deployed internally for reasons of data security and computational control. The model was prompted with a multi-label classification prompt, allowing it to assign tasks to one or more categories simultaneously. In Figure 10, we provide the prompt used to classify the evaluation benchmark to specific topics in cyber security. The results of our classification process detailed in Table 4 and is also visualized in Figure 4.

This choice was intentional: many real-world cybersecurity problems span across multiple domains (e.g., a phishing campaign may involve HumanSec, IAM_ZT, and ThreatOps_IR simultaneously). Restricting classification to single-label outputs would fail to capture these cross-cutting concerns.

Table 4: Counts by dataset and taxonomy category.

dataset	GCR	NetSec	AppSec	CloudSec	IAM_ZT	SecOps	ThreatOps_IR	CryptoSec	HumanSec	Other
CTIBench-MCQ	404	516	935	90	315	422	1409	112	64	11
CTIBench-RCM	87	28	1995	7	68	214	389	52	6	0
SecEval	706	620	1099	117	499	300	370	569	98	18
CyberMetric-2000	722	563	250	37	253	182	304	373	172	119
CISSP Exams	102	42	16	0	26	20	30	20	18	22
Weakness Impact Mapping	62	11	332	0	61	3	26	29	4	6
CTI Detect & Mitigate	219	213	511	21	115	220	421	37	21	2
Adv. CTI	32	111	78	52	90	88	676	24	27	0
CTI Relationship Prediction	203	139	507	10	92	82	348	31	21	0
TOTAL	**2537**	**2243**	**5723**	**334**	**1519**	**1531**	**3973**	**1247**	**431**	**178**

C.2.3 PROMPT VALIDATION USING SECEVAL CATEGORIES

To ensure the robustness and correctness of our classification prompt, we performed a validation against SecEval categories. Specifically, we tested whether the outputs of our multi-label classification aligned with SecEval's category definitions and coverage. This served as a quality assurance step for our classification pipeline. See Table 5 for agreement results between our classification pipeline and SecEval.

Through this process, we confirmed that the OSS-120B model, when guided by our taxonomy-driven prompt, consistently produced category assignments that were both internally coherent and externally validated against widely recognized benchmarks.

Table 5: Validation of our classification pipeline on SecEval categories and data sources, which were also classified using an OpenAI model (gpt-4o). We observe strong overall agreement with SecEval's classifications.

Category Summary	Aligned %
ApplicationSecurity	83.7
Cryptography	100.0
MemorySafety	99.9
NetworkSecurity	97.6
PenTest	87.1
SoftwareSecurity	97.1
SystemSecurity	88.4
Vulnerability	93.8
WebSecurity	84.4

D EVALUATION TEMPLATES AND PROMPTS

In Figure 11 we provide the prompt used for our evaluation process. Since we have both multi-choice as well as classification tasks, we replace the <EXPL>token with the specifics of each question type.

Table 6: Ablation studies full results.

Model	CTI Bench MCQ	CTI Bench RCM	SecEval	Cyber Metric 2000	CISSP Exams	Adv. CTI	Weakness Impact Mapping	CTI Detect & Mitigate	CTI Relationship Prediction	Avg.
Qwen3-4B	61.88	49.95	57.38	87.40	79.80	64.51	57.02	60.77	67.99	65.19
SecKnowledge (Original)	65.45	57.80	49.15	**88.40**	**85.35**	**79.86**	62.75	62.84	65.94	68.60
Baseline Reformatting	63.92	61.65	49.84	87.40	81.81	76.05	63.04	**65.51**	**81.10**	70.04
CyberPal2.0-4B	**69.70**	**81.15**	**59.02**	87.80	80.80	68.03	**66.48**	64.03	77.12	**72.68**

E Ablation Studies Additional Results

This section provides additional ablation results. In Table 6, we report full results for the model trained on the original SecKnowledge dataset and for the model trained with the standard reformatted alignment method Fan et al. (2024). All models were trained on Qwen3-4B-base. We follow the same training recipe described in Section 4.1 for all models. Evaluation follows the protocol in Section 4.3: we use the prompt from Figure 11, extract final answers with regular expressions, and evaluate in a zero-shot setting with temperature set to zero.

F LLMaaJ Experiment details and additional results

To assess answer quality, we used *LLM-as-a-Judge* (LLMaaJ) (Zheng et al., 2023). Thirty cybersecurity experts authored 115 open-ended questions: spanning command-line risk assessment, enterprise security, general cybersecurity, network security, and CTI-related topics. Specifically, the security experts constructed 20 questions related cyber threat intelligence, 20 questions related to security vulnerabilities, 20 questions related to network security, 16 general security questions, 20 questions related to enterprise security, and 19 questions related to command line risk assessment.

Pairwise comparison with grounding — The judge receives a question, two answers, and a carefully collected grounding documents that contains all relevant information to answer the question. The judge should decide which answer is better. The prompt provided to the LLMaaJ is provided in Figure 12 .

Evaluation process — We use OpenAI's o3 (OpenAI, 2025) as the LLM-as-a-judge. The judge evaluates each answer pair along six dimensions —*Contextual Accuracy* (highest priority), *Helpfulness*, *Relevance*, *Conciseness*, *Completeness*, and *length bias* (Gu et al., 2024) then issues a verdict: A better than B, B better than A, tie, or both bad. To mitigate positional bias in LLM-as-a-judge settings (Wang et al., 2023; Zheng et al., 2023), we run the comparison twice with the answers swapped. For each permutation, a model receives a score of 3 if its answer is preferred by the judge, 1 for tie, and 0 for loss; if the preferences flip across orders, the pair will effectively contribute 0 as $3 - 3 = 0$. We also record ties and losses separately, though these were rare in our experiments.

Alignment with human preferences — To validate the judge, we measured agreement with Thirty cybersecurity human experts and found that, with proper grounding, o3 aligns with human preferences in over 90% of cases. Without proper grounding, alignment decreases to 80%.

In Figure 6, we report our LLMaaJ results across all questions. Additionally, in Figures 13, 14, and 15 we report LLMaaJ results per category. As can be observed, our model is preferable by a large margin across all the tested categories.

G Model Quantization

As a deployment-oriented baseline, we also evaluated quantization using bitsandbytes (Dettmers et al., 2022) by loading models directly in 8-bit and 4-bit modes, without any calibration or advanced schemes which are shown to perform better than out-of-the-box quantization (Frantar et al., 2022).

Across our evaluation suite, 8-bit loading resulted in a negligible drop of 0.36% for the 4B model and 0.84% for the 8B model — relative to full precision. Moving to 4-bit, both models saw a larger drop around 4% absolute for the 8B model and 2.78% for the 4B model. Importantly, both quantized modes remained clearly superior to the instruction-tuned baseline, which was not trained using the SecKnowledge 2.0 pipeline. These results suggest that the benefits of fine-tuning largely persist under straightforward low-precision inference, with 8-bit serving as a particularly safe, low-overhead option for memory-constrained deployment and 4-bit serves as a good choice for fast inference or low resource settings, while still keeping high cyber security knowledge.

Table 7: Quantization results. Cells in quantized rows show Δ value with (arrow $\downarrow$ OR $\uparrow$) , where Δ=|Full − Quantized|.

Model	CTI MCQ	CTI RCM	SecEval	Cyber Metric	CISSP	Adv. CTI	Weakness Impact Mapping	CTI Detect & Mitigate	CTI Relationship Prediction	Avg.
4B models										
Qwen 3-4B	61.88	49.95	57.38	87.40	79.80	64.51	57.02	60.77	67.99	65.19
CyberPal 2.0	69.70	81.15	59.02	87.80	80.80	68.03	66.48	64.03	77.12	72.68
CyberPal 2.0 (8-bit)	(↓0.39)	(↑0.60)	(↓1.00)	(↓0.75)	(↓1.51)	(↑0.15)	(↓0.28)	(↓1.18)	(↑1.15)	(↓0.36)
CyberPal 2.0 (4-bit)	(↓3.88)	(↓4.15)	(↓4.11)	(↓4.6)	(↓3.54)	(↑0.85)	(↓3.73)	(↓3.16)	(↑1.28)	(↓2.78)
8B models										
Qwen 3-8B	63.13	63.25	56.19	88.45	83.33	64.93	53.58	59.88	60.67	65.93
CyberPal 2.0	75.15	85.95	66.93	89.85	88.89	87.61	71.06	70.26	87.66	80.37
CyberPal 2.0 (8-bit)	(↓1.08)	(↓1.10)	(↑1.78)	(0.00)	(↓3.03)	(↓2.11)	(↑0.57)	(↓1.68)	(↓0.9)	(↓0.84)
CyberPal 2.0 (4-bit)	(↓4.65)	(↓3.10)	(↓2.97)	(↓3.35)	(↓3.54)	(↓9.44)	(↑2.01)	(↓4.45)	(↓3.86)	(↓4.15)

H USE OF LARGE LANGUAGE MODELS (LLMS)

When writing the paper, we used LLMs to help us find grammar errors and polish sentences that needed further clarifications. No further usage was done using LLMs while writing the paper.

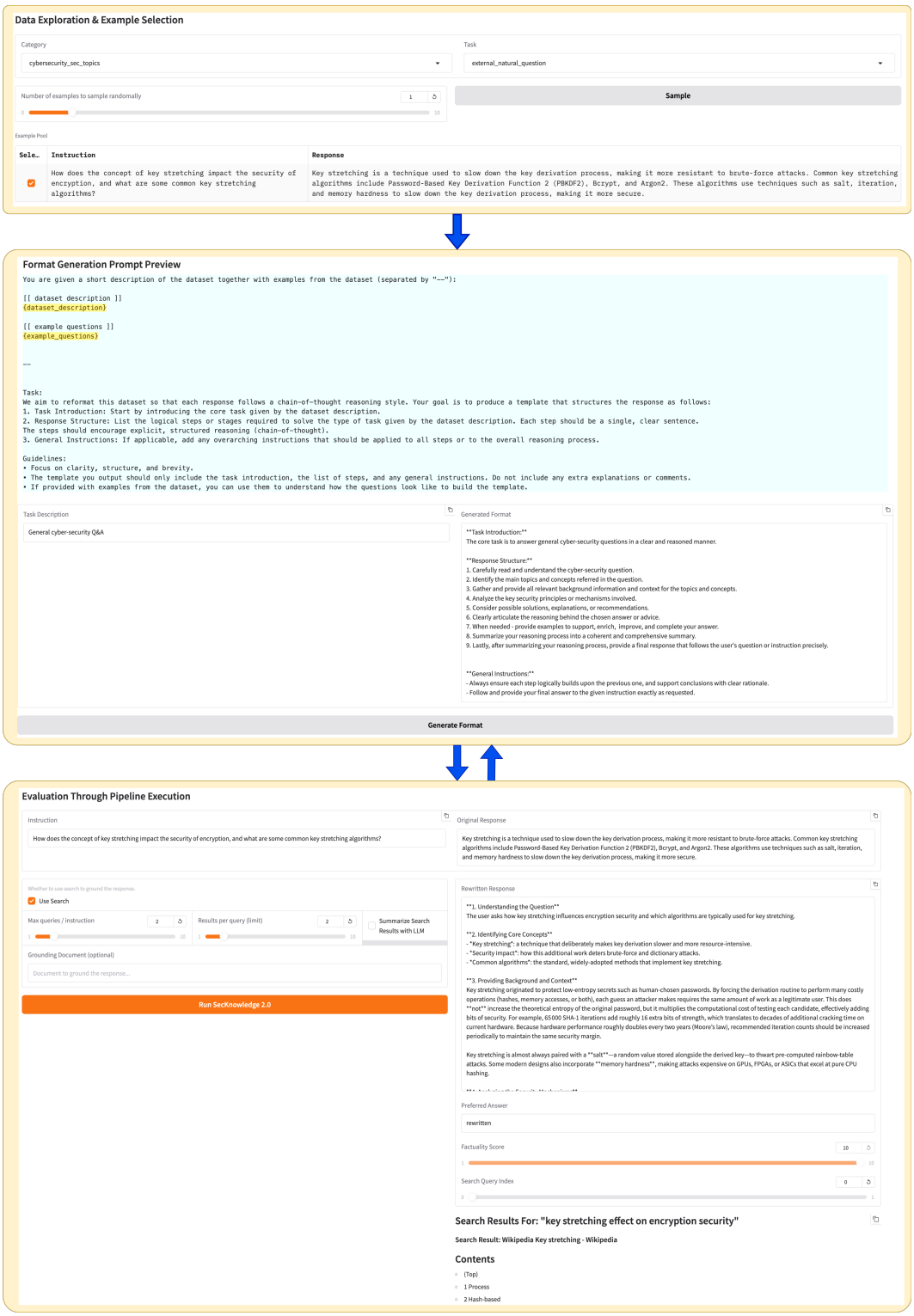

Figure 8: Screenshots from the UI designed for our format generation framework. First, the relevant task is selected, and random examples are sampled from the task data partition, then a candidate format is generated from them using a LLM and the prompt in blue, afterwards an expert can configure and run the pipeline, and edit the format if needed. The UI was developed using Gradio[2].

Figure 9: Data generation quality assessment scores for *SecKnowledge 2.0*, broken down by task. Each bar is color-coded to indicate **readability** outcomes (green for rewritten, red for original, orange for tie, and gray for position inconsistency). The boxes to the right of each bar shows the context requirements (blue box for a task that requires web search, brown box for a task that requires a grounding document), and the number to the right of those boxes denotes the average **factuality** score. The framed labels above groups of tasks indicates their parent category (categories ending with "Evol" contain examples synthetically generated by the second phase of *SecKnowledge*). The number in parentheses after each category indicates how many tasks belong to that category, while the number in parentheses after each task represents the count of instructions within that task.

You are a cybersecurity expert with deep knowledge across all domains of cybersecurity.
Your task is to assign each cybersecurity evaluation benchmark question to one or more predefined categories, using only the question text and its suggested answer options.

Important:
A question may belong to more than one category.
You must provide a brief explanation for each category decision.
Output must strictly follow the JSON format below.

Cybersecurity Categories:

Category 1: GCR
sub_categories:
- Risk Management & Security Strategy
- Compliance and Regulations (e.g., GDPR, HIPAA)
- Security Frameworks (e.g., NIST CSF, ISO 27001)
- Security Policies & Architecture

Category 2: NetSec
sub_categories:
- Perimeter and Network Security (Firewalls, VPNs, Wireless)
- Endpoint Protection & MDM
- IoT and OT/ICS Security
- Mobile Security

Category 3: AppSec
sub_categories:
- Secure Software Development (DevSecOps)
- Application & API Security
- Vulnerability Management & Penetration Testing
- Software Supply Chain Security (SBOM, third-party risk)

Category 4: CloudSec
sub_categories:
- Cloud Security Architecture & Tools
- Identity and Access Management (IAM, PAM)
- Data Loss Prevention & Privacy (DLP, encryption)
- Cloud Compliance & Shared Responsibility Model

Category 5: IAM_ZT
sub_categories:
- Authentication & Authorization (MFA, SSO, RBAC)
- Identity Governance & Lifecycle
- Zero Trust Architecture
- Privileged Access Controls

Category 6: SecOps
sub_categories:
- SIEM, SOC, and Log Management
- Security Automation & SOAR
- Detection Engineering
- Operational Resilience & Monitoring

Category 7: ThreatOps_IR
sub_categories:
- Threat Detection, Analysis & Hunting
- Threat Intelligence Platforms & IOCs
- Advanced Persistent Threats (APTs)
- Malware Techniques
- Incident Response, Recovery & Digital Forensics

Category 8: CryptoSec
sub_categories:
- Cryptographic Algorithms & PKI
- Key Management
- Post-Quantum Cryptography
- Secure Protocols and Encryption Practices

Category 9: HumanSec
sub_categories:
- Social Engineering Techniques (Phishing, Pretexting)
- Insider Threat Management
- Security Awareness Training
- Behavioral Risk Analysis

Category 10: Other

Input format:

Here is the question:
Choose the correct option for the following question: Which of the following mitigations involves preventing applications from running that haven't been downloaded from legitimate repositories?
A: Audit
B: Execution Prevention
C: Operating System Configuration
D: User Account Control

Here is the answer:
B

Output format:

```
{
   explanation_GCR: "reasoning here", "GCR": "yes/no",
   explanation_NetSec: "reasoning here", "NetSec": "yes/no",
   explanation_AppSec: "reasoning here", "AppSec": "yes/no",
   explanation_CloudSec: "reasoning here", "CloudSec": "yes/no",
   explanation_IAM_ZT: "reasoning here", "IAM_ZT": "yes/no",
   explanation_SecOps: "reasoning here", "SecOps": "yes/no",
   explanation_ThreatOps_IR: "reasoning here", "ThreatOps_IR": "yes/no",
   explanation_CryptoSec: "reasoning here", "CryptoSec": "yes/no",
   explanation_HumanSec: "reasoning here", "HumanSec": "yes/no",
   explanation_FutureSec: "reasoning here", "FutureSec": "yes/no",
   explanation_Other: "reasoning here", "Other": "yes/no",
}
```

Figure 10: The prompt used to classify the examples in SecKnowledge 2.0 into cybersecurity topics

You must produce TWO sections for you answer in this exact order:
1) Explanation — a logical step by step rationale for choosing the correct option.
2) '#### Final Answer: {TOKEN}' — a single line with the final answer, <EXPL>.

Formatting rules:
- Start with the line: 'Explanation:'.
- Write the explanation for selecting the correct option.
- The last line MUST be exactly: '#### Final Answer: {TOKEN}'.

Output template (follow literally):
Explanation:
<your explanation>
Final Answer: {TOKEN}

Figure 11: The prompt used to guide the LLMs during the evaluation process. <EXPL> refers to the specific task type (multi-choice, classification, etc.) and is replaced at runtime with explanation about the format of the specific question.

Act as an impartial and meticulous evaluator tasked with assessing the quality of responses provided by two AI assistants to the user prompt outlined below.
You will receive responses from Assistant A and Assistant B. Your responsibility is to determine which assistant's response is superior by conducting a thorough analysis based on the provided criteria.

Evaluation Process:
1. **Contextual Accuracy (Highest Priority):**
- Verify the correctness of the responses with respect to the user Question and provided Context.
- Identify any inaccuracies, errors, or misinterpretations. Responses with factual inaccuracies or contradictions to the given Context are heavily penalized.

2. **Helpfulness:**
- Assess whether the response appropriately addresses the user's prompt or instructions.

3. **Relevance:**
- Determine if all parts of the response align closely with the user's question or request.
- Penalize extraneous or off-topic information.

4. **Conciseness:**
- Evaluate the clarity and brevity of the response.
- Ensure the assistant avoids unnecessary verbosity while maintaining the completeness of the answer.

5. **Completeness:**
- Identify if any important information is missing in the assistants' answers that would be beneficial to include when responding to the user prompt.

6. **Avoid answers' length bias:**
- Do not favor a specific answer simply because it is longer. Choose the better answer based on correctness.

Remember:
* **Primary Criterion:** The most important factor is how accurately each answer reflects the content, reasoning, and details of the provided Context. The answer closest to the Context—both in terms of factual correctness and conceptual alignment—should be preferred.
* **Secondary Criteria:** While Helpfulness, Relevance, and Completeness are important, they should only influence your decision when both answers are equally close to the Context.
* **Do not prefer longer answers:** You should not prefer a specific answer simply since it is longer. Judge the answers based on the previous steps, but do not be biased to longer answers.

Final Verdict:
After analyzing the responses based on the criteria above, provide a concise explanation supporting your judgment. Conclude with one of the following verdicts:

1. Assistant A is better: [[A>B]]
2. Assistant B is better: [[B>A]]
3. Tie: [[A=B]]
4. Both assistants failed to answer correctly: [[B<>A]]

Example Final Verdict: "My final verdict is a Tie: [[A=B]]"

Figure 12: LLM-as-Judge prompt used for pairwise comparison.

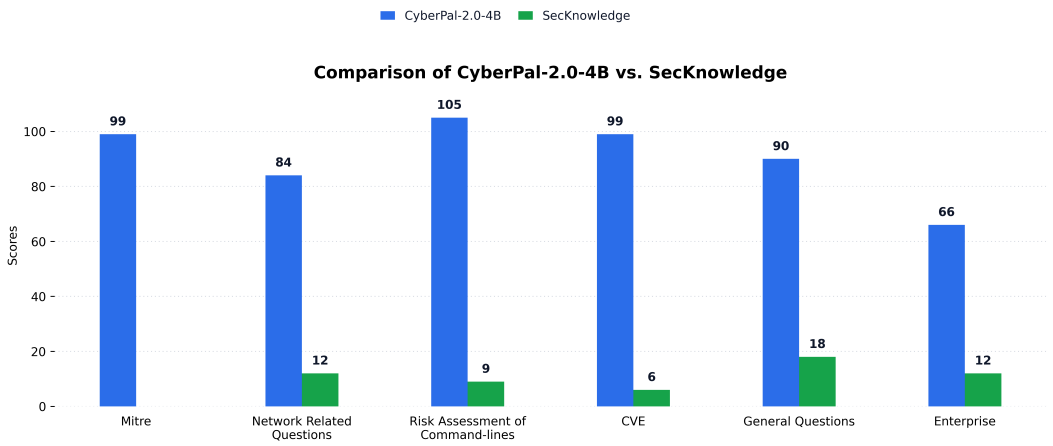

Figure 13: LLM-as-Judge pairwise comparison per category: *CyberPal-2.0-4B* vs. *SecKnowledge*.

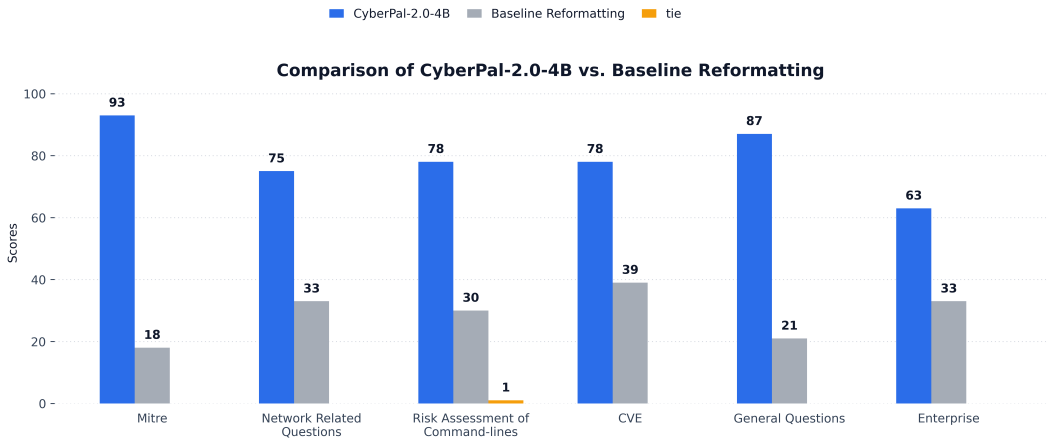

Figure 14: LLM-as-Judge pairwise comparison per category: *CyberPal-2.0-4B* vs. *Baseline Reformatting*.

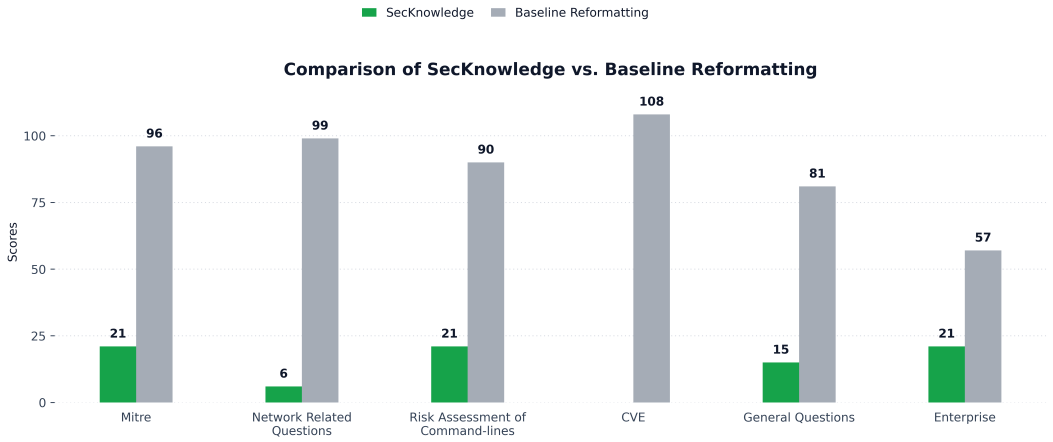

Figure 15: LLM-as-Judge pairwise comparison per category: *SecKnowledge* vs. *Baseline Reformatting*.