RLM Algorithm: Implementation vs. Paper Comparison

Comparison of our `rlm-loop` implementation against the original MIT CSAIL paper (arXiv:2512.24601).

Our Algorithm (as implemented)

```
User Query + Context (file/dir/string)


1. Materialize context → plain Python str
2. Optionally build "context sample" (--no-context-sample disables)
3. Create depth-tracked llm_query(snippet, task) closure (max_depth=3)
4. Initialize REPLEnv with namespace: CONTEXT, FILES, llm_query, FINAL,
   SHOW_VARS, pre-imported modules


5. [Context Engineer - pre_loop] (if --context-engineer-mode includes pre_loop)
   Analyze document sample → produce "document brief" (200-500 words)
   Optionally share brief with root LM (--share-brief-with-root)


6. Send to LLM: system prompt (full/compact) + user query [+ context sample]
   [+ document brief if share_brief_with_root]


   RLM Loop (max_iterations, timeout, token budget)

    7. Check timeout / token budget guards
    8. LLM responds with markdown
    9. Extract ```python blocks (regex)
   10. If no code blocks:
         - Check for "FINAL" in text → done
         - Else prompt LLM to write code
   11. Execute each code block sequentially
         in persistent REPL namespace
            llm_query(snippet, task):
             a. [Context Engineer - per_query]
                (if mode includes per_query)
                Produce context note from
                surrounding text
             b. Sub-RLM receives:
                [document brief] +
```

```
              [context note] +
              snippet + task
           c. Returns plain text
  12. If FINAL() called → done
  13. Feed captured print() output back
        as user message: "Output:\n..."
  14. Continue loop
```

```
Return RLMResult(answer, stats, history)
```

Key files: `rlm/rlm.py` (orchestrator), `rlm/repl.py` (REPL environment), `rlm/prompts.py` (system prompts), `rlm/backends.py` (LLM backends)

LLM Role Interaction (Sequence Diagram)

Shows the full interaction between all four LLM roles during a single `completion()` call with `context_engineer_mode="both"`, `share_brief_with_root=True`, and `verify=True` (all features enabled).

```
sequenceDiagram
    actor User
    participant O as RLM Orchestrator
    participant CE as Context Engineer
    participant Root as Root LM
    participant REPL as REPL Environment
    participant Sub as Sub-RLM
    participant V as Verifier

    User->>O: completion(context, query)

    Note over O: _setup_completion()

    O->>O: Create REPL + llm_query closure
    O->>O: Build document sample<br/>(4 × 600-char excerpts)

    rect rgb(240, 248, 255)
        Note over O,CE: Context Engineer - pre_loop<br/>(if mode = pre_loop | both)
        O->>CE: system: CE_PRE_LOOP_PROMPT<br/>user: query + document sample
        CE-->>O: Document brief (200-500 words)
        O->>O: Bind brief to llm_query closure
        Note over O: If share_brief_with_root:<br/>prepend brief to root user prompt
    end

    O->>O: Build messages:<br/>[system_prompt, user_prompt + sample + brief?]
```

```
loop Main iteration loop (max_iterations, timeout, token budget)
    O->>O: Check guards (timeout, token budget)

    O->>Root: messages (full conversation history)
    Root-->>O: Response with ```python``` blocks

    O->>O: Extract code blocks (regex)

    alt No code blocks found
        alt "FINAL" in response text
            Note over O: Break loop
        else
            O->>O: Append "Please provide Python code"
            Note over O: Continue loop
        end
    else Code blocks found
        O->>REPL: Execute code blocks sequentially

        opt Code calls llm_query(snippet, task)
            rect rgb(255, 248, 240)
                Note over REPL,CE: Context Engineer - per_query<br/>(if mode = per_query
                REPL->>O: llm_query(snippet, task)
                O->>O: Locate snippet in CONTEXT<br/>(find first 200 chars)
                O->>O: Extract ~500 chars before + after
                O->>CE: system: CE_PER_QUERY_PROMPT<br/>user: task + position + surround
                CE-->>O: Context note (50-150 words)
            end

            rect rgb(240, 255, 240)
                Note over O,Sub: Sub-RLM call
                O->>Sub: system: SUB_RLM_PROMPT<br/>user: [brief] + [context note] + sni
                Sub-->>O: Plain text analysis
            end
            O-->>REPL: Return sub-RLM response
        end

        REPL-->>O: Execution output (print + final_answer?)

        alt FINAL() called
            Note over O: Break loop → finalize
        else No FINAL yet
            O->>O: Append output to messages:<br/>"Output:\n{output}"
            Note over O: Continue loop
        end
    end
```

```
    end

    rect rgb(248, 240, 255)
        Note over O,V: Verification (if --verify)
        O->>V: system: VERIFIER_PROMPT<br/>user: answer + first 5000 chars of context
        V-->>O: "VERIFIED" or "ISSUES: ..."
        Note over O: Append issues note<br/>if verification fails
    end

    O-->>User: RLMResult(answer, stats, history)
```

Data Flow Between Roles

Shows what data each role receives and produces, and how outputs flow to downstream consumers.

```
flowchart TD
    Q[User Query + Context] --> O[RLM Orchestrator]

    O -->|document sample + query| CE_PRE["Context Engineer<br/>(pre-loop)"]
    CE_PRE -->|document brief| O

    O -->|system prompt + user prompt<br/>+ sample + brief  | ROOT[Root LM]
    ROOT -->|Python code| REPL[REPL Environment]
    REPL -->|print output| ROOT

    REPL -->|snippet + task| CE_PQ["Context Engineer<br/>(per-query)"]
    CE_PQ -->|context note| SUB[Sub-RLM]

    O -.->|document brief| SUB
    REPL -->|snippet + task| SUB
    SUB -->|plain text| REPL

    ROOT -->|"FINAL(answer)"| O
    O -->|answer + evidence| V[Verifier]
    V -->|verdict| O
    O -->|RLMResult| U[User]

    style CE_PRE fill:#e8f4fd,stroke:#4a90d9
    style CE_PQ fill:#fff3e0,stroke:#f5a623
    style ROOT fill:#e8f5e9,stroke:#4caf50
    style SUB fill:#e8f5e9,stroke:#81c784
    style V fill:#f3e5f5,stroke:#ab47bc
    style REPL fill:#fff9c4,stroke:#fbc02d
```

Legend

Arrow	Meaning
brief	Only if `--share-brief-with-root`
Solid line	Always active when the role is invoked
Dashed line	Conditional on `context_engineer_mode`

What each role sees

Role	System Prompt	User Message Contains	Produces
Context Engineer (pre-loop)	Document analysis specialist prompt	Query + 4 × 600-char document excerpts	Document brief (200–500 words)
Context Engineer (per-query)	Context note specialist prompt	Task + snippet position + ~500 chars before/after	Context note (50–150 words)
Root LM	Full strategy prompt (Inspect→Search→Chunk→Synthesize)	Query + document sample [+ brief]	Python code in ```` ```python ```` blocks
Sub-RLM	Minimal text-analysis prompt	[Brief] + [context note] + snippet + task	Plain text (summary, extraction, etc.)
Verifier	Verification prompt	Proposed answer + first 5000 chars of context	"VERIFIED" or "ISSUES: …"

Paper's Algorithm

```
User Query + Context


1. Store context as CONTEXT variable in Python REPL
2. Provide llm_query(snippet, task) for sub-RLM calls
3. Root LM receives ONLY the query (context is not inline)


4. Send to LLM: system prompt + query (no context sample)
```

```
Code-Observe-Reason Loop

5. LLM generates Python code
6. Execute in REPL sandbox
7. Observe output (truncated)
8. LLM decides next action:
     - More code (inspect/search/chunk)
     - llm_query() for semantic analysis
     - FINAL(answer) when confident
9. Continue loop
```

```
Return final answer
```

Side-by-Side Comparison

Aspect	Paper	Our Implementation	Delta
Initial context exposure	Root LM sees only the query; CONTEXT is opaque until code runs	Context sample included by default; `--no-context-sample` disables it	**Aligned** — can now match paper's opaque-context design via flag
`llm_query` signature	`llm_query(snippet, task)` — two args	`llm_query(snippet, task)` — two args	**Match**
Recursive depth	Depth-1 only (root → sub-RLM, no deeper)	Configurable `max_depth=3` (supports multi-level recursion)	We're ahead of the paper here
Sub-RLM model	Smaller/cheaper model for sub-calls (e.g., GPT-5-mini when root is GPT-5)	`--sub-rlm-model` param exists but defaults to same model as `--model`; per-role backends/models via `--config` YAML	Paper's design is more cost-efficient; config file enables it

Aspect	Paper	Our Implementation	Delta
System prompt for sub-calls	Not detailed	Minimal task-focused system prompt (text analysis role)	Aligned — sub-calls now receive focused guidance
Termination	`FINAL()` + max iterations + timeouts	`FINAL()` + max iterations + `--timeout` + `--max-token-budget`	**Match**
Default model	Not applicable (paper uses specific models per experi- ment)	`--model` is required (no defaults)	**Aligned** — user must choose explicitly
Code extraction	Not specified in detail	Regex: `` ```python\n(.*?)``` `` — only explicitly tagged Python blocks	Reasonable; ignores non-Python fenced blocks
Structured output	Not discussed (implicitly uses free-form text)	`LLMBackend.supports_structured_output` property (default `False`); `StructuredResponse` dataclass and `STRUCTURED_RESPONSE_SCHEMA` for JSON-schema mode; `CompletionResult.structured` carries parsed response when available; `OpenAICompatibleBackend` implements `structured_completion()` via `response_format={"type": "json_object"}` with graceful fallback on malformed JSON	Extension beyond the paper; OpenAI-compatible backends now support it, Anthropic backend pending
Sandbox isolation	Rootless container (security delegated to runtime)	Safe builtins whitelist (no `__import__`, `open`, `exec`) + container delegation	We add in-process restrictions on top of container isolation

Aspect	Paper	Our Implementation	Delta
Output truncation	Mentioned (first ~10K chars)	10,000 char cap per execution	Match
Multi-file support	Not discussed	`FILES` dict + `CompositeContext` for directories	Extension beyond the paper
Context loading	Context as string	Memory-mapped files via `LazyContext`, `CompositeContext` for multi-file	Engineering refinement beyond the paper
Async execution	Identified as future work	Stubs exist (`acompletion`) but delegate to sync	Neither implements true async
Native post-training	RLM-Qwen3-8B (28.3% improvement over base)	Prompt-only, no fine-tuning	Paper has a training component we don't
Cost tracking	Discussed (comparable median, high variance tail)	`RLMStats` tracks tokens, iterations, sub-RLM calls; `--max-token-budget` enforces limits	**Aligned** — cost enforcement now available
Verification strategy	Some models perform redundant verification sub-calls	`--verify` flag enables explicit verification sub-call on the final answer	Paper observes this as emergent behavior; we formalize it as opt-in
Sub-RLM context	Sub-RLM receives only snippet + task (no document context)	Context-engineer role can provide document brief and per-query context notes to sub-RLM calls	Extension beyond the paper; opt-in via `--context-engineer-mode`

LLM Roles

The RLM pattern uses up to four distinct LLM roles with different responsibilities:

Role Comparison

Aspect	Root LM	Sub-RLM	Verifier	Context Engineer
Depth	0	1+ (up to `max_depth`)	0 (post-processing)	0 (pre-processing / per-query)
System prompt	Full strategy prompt (~120 lines) or compact (~25 lines)	Minimal task-focused prompt	Verification-focused prompt	Pre-loop: document analysis prompt; Per-query: context note prompt
Conversation	Multi-turn (code → output → code → … → FINAL)	Single-turn (one prompt, one response)	Single-turn	Single-turn (per invocation)
Produces	Python code in ` ```python ` blocks	Plain text (summary, extraction, analysis)	VERIFIED or ISSUES: …	Document brief (pre-loop) or context note (per-query)
Has access to	`CONTEXT`, `FILES`, `llm_query()`, `FINAL()`, `SHOW_VARS()`, pre-imported modules	Only the snippet passed by root + optional brief/note	Proposed answer + evidence	Document sample (pre-loop) or snippet + surrounding text (per-query)
Model	`--model`	`--sub-rlm-model` (defaults to `--model`)	Config only (defaults to sub-RLM model)	Config only (defaults to sub-RLM model)
Backend	`--backend` or config	Config only (defaults to root's)	Config only (defaults to root's)	Config only (defaults to root's)

Aspect	Root LM	Sub-RLM	Verifier	Context Engineer
Custom prompt	Via `--config roles.root.system_prompt`	Via `--config roles.sub_rlm.system_prompt`	Via `--config roles.verifier.system_prompt`	Via `--config roles.context_engineer.system_prompt` (pre-loop) and `per_query_prompt`

Root LM Responsibilities

The root LM writes Python code to explore the document programmatically. It never sees the full document inline (unless `--no-context-sample` is disabled). Instead, it:

1. Receives the user query (and optionally a document sample)
2. Writes exploration code to inspect structure, search for patterns, extract chunks
3. Delegates **semantic** analysis to the sub-RLM via `llm_query(snippet, task)`
4. Aggregates sub-RLM results and calls `FINAL(answer)` when confident

Sub-RLM Responsibilities

The sub-RLM processes individual text chunks. It:

1. Receives a snippet of text and a task description
2. Returns plain-text results (summaries, extractions, classifications)
3. Has no access to the REPL, `CONTEXT`, or any tools — only the snippet it was given
4. Does not generate code

Emergent Strategies from the Paper

The paper (arXiv:2512.24601) and the accompanying blog post identify five emergent strategies that models discover when given the RLM environment:

Strategy	Description	Example Code
Peeking	Inspect document structure and size	`print(CONTEXT[:1000])`, `print(len(CONTEXT))`
Grepping	Keyword/regex search to locate relevant regions	`re.findall(r'pattern', CONTEXT, re.IGNORECASE)`
Partition+Map	Chunk the document and fan out `llm_query()` calls	Split `CONTEXT` into N chunks, call `llm_query()` on each

Strategy	Description	Example Code
Summarization	Hierarchical summarization via sub-RLM calls	Summarize chunks, then summarize the summaries
Long-input/long-output	Direct extraction for structured outputs	Extract lists, tables, or formatted data from large regions

Our prompts map these emergent strategies to a prescriptive four-phase model:

Our Phase	Paper Strategies Covered
Inspect	Peeking
Search	Grepping
Chunk + Analyze	Partition+Map, Summarization
Synthesize	Long-input/long-output, final aggregation

The paper observes that models discover these strategies naturally with minimal prompting. Our prompts are more prescriptive (explicit chunk size guidance, specific function examples), which improves consistency but may constrain creative exploration.

Context Engineer (Extension Beyond Paper)

The paper's sub-RLM calls operate in complete isolation — each `llm_query(snippet, task)` gives the sub-RLM only the snippet and task, with no knowledge of the document's type, structure, terminology, or where the snippet sits. This limits sub-RLM accuracy for domain-specific documents (legal contracts, research papers, technical specs).

Our context-engineer role addresses this limitation with two configurable intervention points:

Mode	When	LLM Calls	What it does
`off`	Never (default)	0	Current behavior, matches paper
`pre_loop`	Before main loop	1	Produces document brief from sample
`per_query`	Before each `llm_query()`	N	Adds surrounding context + position metadata
`both`	Both points	1 + N	Brief + per-query enhancement

Pre-loop analysis (`_run_pre_loop_analysis`): Feeds a document sample to the CE backend and receives a document brief (200-500 words) covering document type, key terminology, structure, important entities, and writing conventions. The brief is then prepended to every sub-RLM call, and optionally shared with the root LM (`--share-brief-with-root`).

Per-query enhancement (`_enhance_per_query`): Before each `llm_query()`, locates the snippet within the full CONTEXT, extracts ~500 chars of surrounding text, and calls the CE backend to produce a context note (50-150 words) about position, terminology references, and relevant background. The note is prepended to the sub-RLM prompt.

The context-engineer defaults cascade from the sub-RLM role (both are "helper" roles), so configuring `sub_rlm` in the YAML config automatically applies to `context_engineer` unless overridden.

Verification (Emergent Behavior)

The paper observes that some models perform redundant "verification" subcalls — re-checking their own intermediate results before calling `FINAL()`. This behavior is emergent and not prompted for. Our implementation offers an explicit `--verify` flag that formalizes this pattern as an opt-in post-processing step.

Remaining Divergences

1. Context Sample in Initial Prompt (our addition, now optional)

Our approach (`_build_context_sample()`): By default, sends evenly-spaced 500-char excerpts from the document in the first message. Can be disabled with `--no-context-sample` to match the paper's opaque-context design.

Paper's approach: Root LM only knows CONTEXT exists. It must write code to inspect it.

Trade-off: The default gives the LLM a head start (knows format, size, structure immediately) but adds tokens to the initial prompt. Use `--no-context-sample` for the paper's strict "context as environment" paradigm.

2. Multi-level Recursion (our extension)

Paper: Depth-1 only (root → sub-RLM, no deeper).

Ours: Configurable `max_depth=3` (supports multi-level recursion).

This is an intentional extension beyond the paper's design.

Emergent Strategy Comparison

Both the paper and our prompts describe the same four-phase strategy:

Phase	Paper	Our Prompts
Inspect	Examine context structure, size, format	If sample provided, study it; otherwise `print(CONTEXT[:1000])`
Search	Regex/keyword filtering to narrow focus	"Start BROAD: `re.findall(pattern, CONTEXT)` with `re.IGNORECASE`"
Chunk	Uniform or semantic partitioning	"Extract sections: `CONTEXT[start:end]` (aim for 1000-5000 chars)"
Synthesize	Aggregate sub-RLM results + FINAL()	"Combine and call `FINAL(answer)`"

Our prompts also include guidance on when to use `llm_query()` (semantic tasks) vs Python directly (structural tasks). The paper observes these strategies as emergent behavior that models discover with minimal prompting; our prompts are more prescriptive to improve consistency.

Future Refinement Candidates

Actionable items identified by this comparison:

- **Default to a cheaper model for sub-RLM calls** — leverage `--sub-rlm-model` param with a smaller default
- **Evaluate prompt prescriptiveness** — test whether our detailed prompts help or constrain the LLM compared to the paper's minimal approach
- **Native post-training** — the paper fine-tuned RLM-Qwen3-8B (28.3% improvement over base); we rely on prompt-only guidance
- **True async execution** — replace sync-delegating `acompletion` stubs with genuine async REPL execution
- **Context-engineer token budget** — CE calls currently draw from the same `max_token_budget`; per-query mode (N calls) can exhaust budget faster; consider separate budgets or adaptive call limits
- **Context-engineer snippet location** — `_enhance_per_query()` uses `context_str.find(snippet[:200])` which can fail if the root LM transforms the snippet; more robust matching (fuzzy, n-gram) could improve hit rate

- **Structured output backend implementations** — `OpenAICompatibleBackend` now implements `structured_completion()` with JSON mode; `AnthropicBackend` still needs its own implementation; orchestrator integration (#14) needed to actually use structured output in the iteration loop