VOYAGER: An Open-Ended Embodied Agent with Large Language Models

Guanzhi Wang[1,2]✉, **Yuqi Xie**[3], **Yunfan Jiang**[4*], **Ajay Mandlekar**[1*], **Chaowei Xiao**[1,5], **Yuke Zhu**[1,3], **Linxi Fan**[1†]✉, **Anima Anandkumar**[1,2†]
[1]NVIDIA, [2]Caltech, [3]UT Austin, [4]Stanford, [5]UW Madison
[*]Equal contribution [†]Equal advising ✉ Correspondence authors
https://voyager.minedojo.org

Abstract

We introduce VOYAGER, the first LLM-powered embodied lifelong learning agent in Minecraft that continuously explores the world, acquires diverse skills, and makes novel discoveries without human intervention. VOYAGER consists of three key components: 1) an automatic curriculum that maximizes exploration, 2) an ever-growing skill library of executable code for storing and retrieving complex behaviors, and 3) a new iterative prompting mechanism that incorporates environment feedback, execution errors, and self-verification for program improvement. VOYAGER interacts with GPT-4 via blackbox queries, which bypasses the need for model parameter fine-tuning. The skills developed by VOYAGER are temporally extended, interpretable, and compositional, which compounds the agent's abilities rapidly and alleviates catastrophic forgetting. Empirically, VOYAGER shows strong in-context lifelong learning capability and exhibits exceptional proficiency in playing Minecraft. It obtains 3.3× more unique items, travels 2.3× longer distances, and unlocks key tech tree milestones up to 15.3× faster than prior SOTA. VOYAGER is able to utilize the learned skill library in a new Minecraft world to solve novel tasks from scratch, while other techniques struggle to generalize.

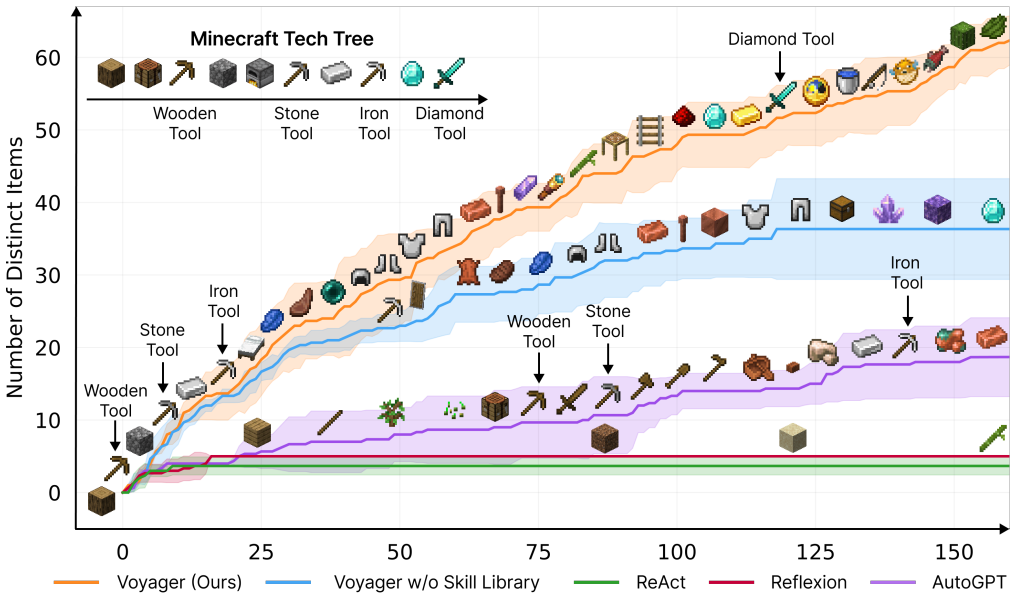

Figure 1: VOYAGER discovers new Minecraft items and skills continually by self-driven exploration, significantly outperforming the baselines. X-axis denotes the number of prompting iterations.

2nd Workshop on Agent Learning in Open-Endedness (ALOE) at NeurIPS 2023.

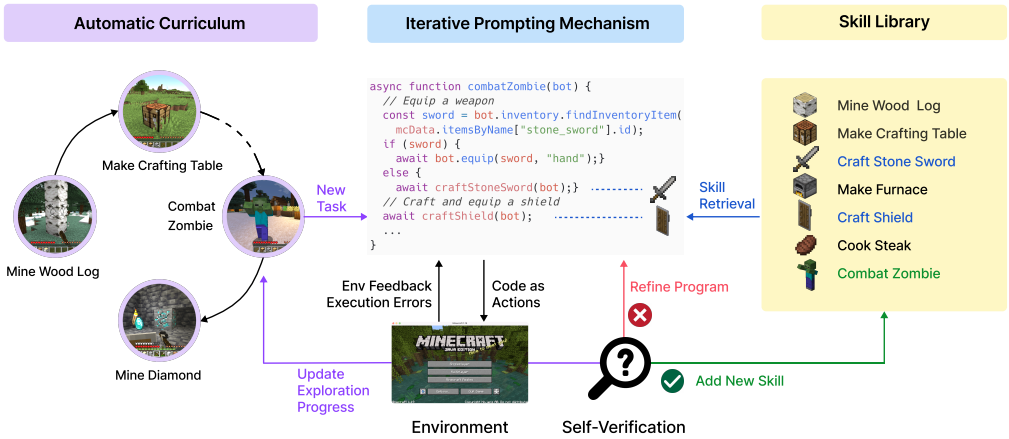

Figure 2: VOYAGER consists of three key components: an automatic curriculum for open-ended exploration, a skill library for increasingly complex behaviors, and an iterative prompting mechanism that uses code as action space.

1 Introduction

Building generally capable embodied agents that continuously explore, plan, and develop new skills in open-ended worlds is a grand challenge for the AI community [1–5]. Classical approaches employ reinforcement learning (RL) [6, 7] and imitation learning [8–10] that operate on primitive actions, which could be challenging for systematic exploration [11–15], interpretability [16–18], and generalization [19–21]. Recent advances in large language model (LLM) based agents harness the world knowledge encapsulated in pre-trained LLMs to generate consistent action plans or executable policies [16, 22, 19]. They are applied to embodied tasks like games and robotics [23–27], as well as NLP tasks without embodiment [28–30]. However, these agents are not lifelong learners that can progressively acquire, update, accumulate, and transfer knowledge over extended time spans [31, 32].

Let us consider Minecraft as an example. Unlike most other games studied in AI [33, 34, 10], Minecraft does not impose a predefined end goal or a fixed storyline but rather provides a unique playground with endless possibilities [23]. Minecraft requires players to explore vast, procedurally generated 3D terrains and unlock a tech tree using gathered resources. Human players typically start by learning the basics, such as mining wood and cooking food, before advancing to more complex tasks like combating monsters and crafting diamond tools. We argue that an effective lifelong learning agent should have similar capabilities as human players: (1) **propose suitable tasks** based on its current skill level and world state, e.g., learn to harvest sand and cactus before iron if it finds itself in a desert rather than a forest; (2) **refine skills** based on environmental feedback and **commit mastered skills to memory** for future reuse in similar situations (e.g. fighting zombies is similar to fighting spiders); (3) **continually explore the world** and seek out new tasks in a self-driven manner.

Towards these goals, we introduce VOYAGER, the first *LLM-powered embodied lifelong learning agent* to drive exploration, master a wide range of skills, and make new discoveries continually without human intervention in Minecraft. VOYAGER is made possible through three key modules (Fig. 2): 1) an **automatic curriculum** that maximizes exploration; 2) a **skill library** for storing and retrieving complex behaviors; and 3) a new **iterative prompting mechanism** that generates executable code for embodied control. We opt to use code as the action space instead of low-level motor commands because programs can naturally represent temporally extended and compositional actions [16, 22], which are essential for many long-horizon tasks in Minecraft. VOYAGER interacts with a blackbox LLM (GPT-4 [35]) through prompting and in-context learning [36–38]. Our approach bypasses the need for model parameter access and explicit gradient-based training or finetuning.

More specifically, VOYAGER attempts to solve progressively harder tasks proposed by the **automatic curriculum**, which takes into account the exploration progress and the agent's state. The curriculum is generated by GPT-4 based on the overarching goal of "discovering as many diverse things as possible". This approach can be perceived as an in-context form of *novelty search* [39, 40]. VOYAGER incrementally builds a **skill library** by storing the action programs that help solve a task successfully.

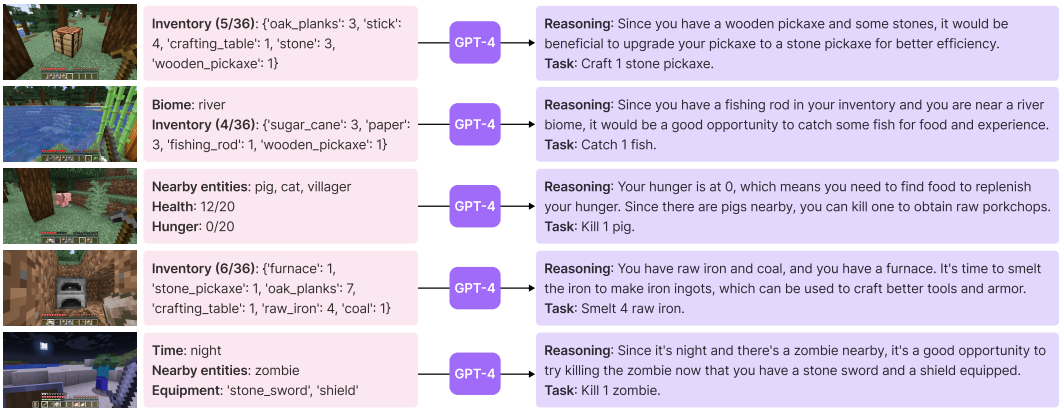

Figure 3: Tasks proposed by the automatic curriculum. We only display the partial prompt for brevity. See Appendix, Sec. A.3 for the full prompt structure.

Each program is indexed by the embedding of its description, which can be retrieved in similar situations in the future. Complex skills can be synthesized by *composing* simpler programs, which compounds VOYAGER's capabilities rapidly over time and alleviates catastrophic forgetting in other continual learning methods [31, 32].

However, LLMs struggle to produce the correct action code consistently in one shot [41]. To address this challenge, we propose an **iterative prompting mechanism** that: (1) executes the generated program to obtain observations from the Minecraft simulation (such as inventory listing and nearby creatures) and error trace from the code interpreter (if any); (2) incorporates the feedback into GPT-4's prompt for another round of code refinement; and (3) repeats the process until a self-verification module confirms the task completion, at which point we commit the program to the skill library (e.g., `craftStoneShovel()` and `combatZombieWithSword()`) and query the automatic curriculum for the next milestone (Fig. 2).

Empirically, VOYAGER demonstrates strong **in-context lifelong learning** capabilities. It can construct an ever-growing skill library of action programs that are reusable, interpretable, and generalizable to novel tasks. We evaluate VOYAGER systematically against other LLM-based agent techniques (e.g., ReAct [29], Reflexion [30], AutoGPT [28]) in MineDojo [23], an open-source Minecraft AI framework. VOYAGER outperforms prior SOTA by obtaining $3.3\times$ more unique items, unlocking key tech tree milestones up to $15.3\times$ faster, and traversing $2.3\times$ longer distances. We further demonstrate that VOYAGER is able to utilize the learned skill library in a new Minecraft world to solve novel tasks from scratch, while other methods struggle to generalize.

2 Method

VOYAGER consists of three novel components: (1) an automatic curriculum (Sec. 2.1) that suggests objectives for open-ended exploration, (2) a skill library (Sec. 2.2) for developing increasingly complex behaviors, and (3) an iterative prompting mechanism (Sec. 2.3) that generates executable code for embodied control. Full prompts are presented in Appendix, Sec. A.

2.1 Automatic Curriculum

Embodied agents encounter a variety of objectives with different complexity levels in open-ended environments. An automatic curriculum offers numerous benefits for open-ended exploration, ensuring a challenging but manageable learning process, fostering curiosity-driven intrinsic motivation for agents to learn and explore, and encouraging the development of general and flexible problem-solving strategies [42–44]. Our automatic curriculum capitalizes on the internet-scale knowledge contained within GPT-4 by prompting it to provide a steady stream of new tasks or challenges. The curriculum unfolds in a bottom-up fashion, allowing for considerable adaptability and responsiveness to the exploration progress and the agent's current state (Fig. 3). As VOYAGER progresses to harder self-driven goals, it naturally learns a variety of skills, such as "mining a diamond".

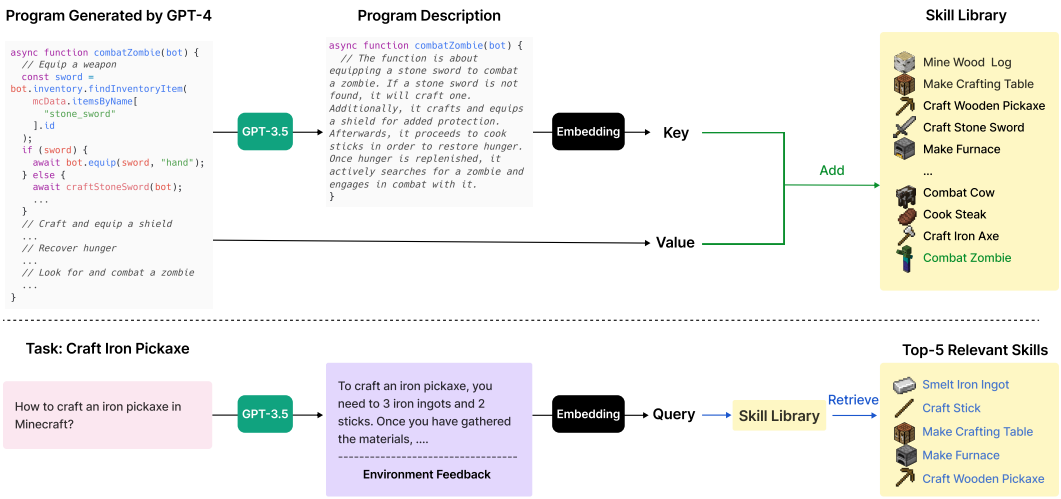

Figure 4: Skill library. **Top: Adding a new skill.** Each time GPT-4 generates and verifies a new skill, we add it to the skill library, represented by a vector database. The key is the embedding vector of the program description (generated by GPT-3.5), while the value is the program itself. **Bottom: Skill retrieval.** When faced with a new task proposed by the automatic curriculum, we first leverage GPT-3.5 to generate a general suggestion for solving the task, which is combined with environment feedback as the query context. Subsequently, we perform querying to identify the top-5 relevant skills.

The input prompt to GPT-4 consists of several components:

(1) **Directives encouraging diverse behaviors and imposing constraints**, such as "`My ultimate goal is to discover as many diverse things as possible ... The next task should not be too hard since I may not have the necessary resources or have learned enough skills to complete it yet.`";

(2) **The agent's current state**, including inventory, equipment, nearby blocks and entities, biome, time, health and hunger bars, and position;

(3) **Previously completed and failed tasks**, reflecting the agent's current exploration progress and capabilities frontier;

(4) **Additional context**: We also leverage GPT-3.5 to self-ask questions based on the agent's current state and exploration progress and self-answer questions. We opt to use GPT-3.5 instead of GPT-4 for standard NLP tasks due to budgetary considerations.

2.2 Skill Library

With the automatic curriculum consistently proposing increasingly complex tasks, it is essential to have a skill library that serves as a basis for learning and evolution. Inspired by the generality, interpretability, and universality of programs [45], we represent each skill with executable code that scaffolds temporally extended actions for completing a specific task proposed by the automatic curriculum.

The input prompt to GPT-4 consists of the following components:

(1) **Guidelines for code generation**, such as "`Your function will be reused for building more complex functions. Therefore, you should make it generic and reusable.`";

(2) **Control primitive APIs, and relevant skills** retrieved from the skill library, which are crucial for in-context learning [36–38] to work well;

(3) **The generated code from the last round, environment feedback, execution errors, and critique**, based on which GPT-4 can self-improve (Sec. 2.3);

Environment Feedback

I cannot make stick because I need: 2 more planks
I cannot make stone_shovel because I need: 2 more stick

GPT-4

```
async function craftStoneShovelWithTable(bot) {
   // If not enough cobblestone, mine cobblestone
   ...
+  // If not enough sticks, check if there are
+  // enough planks in the inventory
   if (sticksCount < 2) {
+    const planksCount = bot.inventory.count(
+      mcData.itemsByName.acacia_planks.id);
+    if (planksCount < 2) {
+      // Collect or craft planks
+      await mineBlock(bot, "acacia_log", 1);
+      await craftItem(bot, "acacia_planks", 1);
+    }
+    // Craft sticks using planks
     await craftItem(bot, "stick", 1);}
   await craftItem(bot, "stone_shovel", 1);
}
```

Execution Error

throw new Error(`No item named ${name}`);
No item named acacia_axe
at line 18:await craftItem(bot, "acacia_axe", 1);

GPT-4

```
-async function craftAcaciaAxe(bot) {
+async function craftWoodenAxe(bot) {
   // Craft anacia planks and sticks
   ...

   // Place the crafting table near the bot
   ...

-  // Craft an acacia axe using 3 acacia planks
-  // and 2 sticks
-  await craftItem(bot, "acacia_axe", 1);
-  bot.chat("Acacia axe crafted.");
+  // Craft a wooden axe using 3 acacia planks
+  // and 2 sticks
+  await craftItem(bot, "wooden_axe", 1);
+  bot.chat("Wooden axe crafted.");
}
```

Figure 5: **Left: Environment feedback.** GPT-4 realizes it needs 2 more planks before crafting sticks. **Right: Execution error.** GPT-4 realizes it should craft a wooden axe instead of an acacia axe since there is no acacia axe in Minecraft. We only display the partial prompt for brevity. The full prompt structure for code generation is in Appendix, Sec. A.4.

(4) **The agent's current state**, including inventory, equipment, nearby blocks and entities, biome, time, health and hunger bars, and position; (5) **Chain-of-thought prompting** [46] to do reasoning before code generation.

We iteratively refine the program through a novel iterative prompting mechanism (Sec. 2.3), incorporate it into the skill library as a new skill, and index it by the embedding of its description (Fig. 4, top). For skill retrieval, we query the skill library with the embedding of self-generated task plans and environment feedback (Fig. 4, bottom). By continuously expanding and refining the skill library, VOYAGER can learn, adapt, and excel in a wide spectrum of tasks, consistently pushing the boundaries of its capabilities in the open world.

2.3 Iterative Prompting Mechanism

We introduce an iterative prompting mechanism for self-improvement through three types of feedback:

(1) **Environment feedback**, which illustrates the intermediate progress of program execution (Fig. 5, left). For example, "`I cannot make an iron chestplate because I need: 7 more iron ingots`" highlights the cause of failure in crafting an iron chestplate. We use `bot.chat()` inside control primitive APIs to generate environment feedback and prompt GPT-4 to use this function as well during code generation;

(2) **Execution errors** from the program interpreter that reveal any invalid operations or syntax errors in programs, which are valuable for bug fixing (Fig. 5, right);

(3) **Self-verification for checking task success.** Instead of manually coding success checkers for each new task proposed by the automatic curriculum, we instantiate another GPT-4 agent for self-verification. By providing VOYAGER's current state and the task to GPT-4, we ask it to act as a critic [47–49] and inform us whether the program achieves the task. In addition, if the task fails, it provides a critique by suggesting how to complete the task (Fig. 6). Hence, our self-verification is more comprehensive than self-reflection [30] by both checking success and reflecting on mistakes.

Figure 6: Self-verification examples. We only display the partial prompt for brevity. See Appendix, Sec. A.5 for the full prompt structure.

During each round of code generation, we execute the generated program to obtain environment feedback and execution errors from the code interpreter, which are incorporated into GPT-4's prompt for the next round of code refinement. This iterative process repeats until self-verification validates the task's completion, at which point we add this new skill to the skill library and ask the automatic curriculum for a new objective (Fig. 2). If the agent gets stuck after 4 rounds of code generation, then we query the curriculum for another task. This iterative prompting approach significantly improves program synthesis for embodied control, enabling VOYAGER to continuously acquire diverse skills without human intervention.

3 Experiments

3.1 Experimental Setup

We leverage OpenAI's `gpt-4-0314` [35] and `gpt-3.5-turbo-0301` [50] APIs for text completion, along with `text-embedding-ada-002` [51] API for text embedding. We set all temperatures to 0 except for the automatic curriculum, which uses temperature $= 0.1$ to encourage task diversity. Our simulation environment is built on top of MineDojo [23] and leverages Mineflayer [52] JavaScript APIs for motor controls. See Appendix, Sec. B.1 for more details.

3.2 Baselines

Because there is no LLM-based agents that work out of the box for Minecraft, we make our best effort to select a number of representative algorithms as baselines. These methods are originally designed only for NLP tasks without embodiment, therefore we have to re-interpret them to be executable in MineDojo and compatible with our experimental setting:

ReAct [29] uses chain-of-thought prompting [46] by generating both reasoning traces and action plans with LLMs. We provide it with our environment feedback and the agent states as observations.

Reflexion [30] is built on top of ReAct [29] with self-reflection to infer more intuitive future actions. We provide it with execution errors and our self-verification module.

AutoGPT [28] is a popular software tool that automates NLP tasks by decomposing a high-level goal into multiple subgoals and executing them in a ReAct-style loop. We re-implement AutoGPT by using GPT-4 to do task decomposition and provide it with the agent states, environment feedback, and execution errors as observations for subgoal execution. Compared with VOYAGER, AutoGPT lacks the skill library for accumulating knowledge, self-verification for assessing task success, and automatic curriculum for open-ended exploration.

Note that we do not directly compare with prior methods that take Minecraft screen pixels as input and output low-level controls [53–55]. It would not be an apple-to-apple comparison, because we rely

Table 1: Tech tree mastery. Fractions indicate the number of successful trials out of three total runs. 0/3 means the method fails to unlock a level of the tech tree within the maximal prompting iterations (160). Numbers are prompting iterations averaged over three trials. The fewer the iterations, the more efficient the method.

Method	Wooden Tool	Stone Tool	Iron Tool	Diamond Tool
ReAct [29]	N/A (0/3)	N/A (0/3)	N/A (0/3)	N/A (0/3)
Reflexion [30]	N/A (0/3)	N/A (0/3)	N/A (0/3)	N/A (0/3)
AutoGPT [28]	92 ± 72 (3/3)	94 ± 72 (3/3)	135 ± 103 (3/3)	N/A (0/3)
VOYAGER w/o Skill Library	$\mathbf{7 \pm 2}$ (3/3)	$\mathbf{9 \pm 4}$ (3/3)	29 ± 11 (3/3)	N/A (0/3)
VOYAGER (Ours)	$\mathbf{6 \pm 2}$ (3/3)	$\mathbf{11 \pm 2}$ (3/3)	$\mathbf{21 \pm 7}$ (3/3)	**102** (1/3)

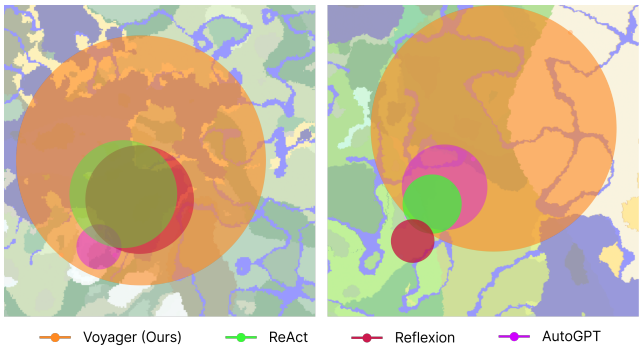

Figure 7: Map coverage: bird's eye views of Minecraft maps. VOYAGER is able to traverse 2.3× longer distances compared to baselines while crossing diverse terrains.

on the high-level Mineflayer [52] API to control the agent. Our work's focus is on pushing the limits of GPT-4 for lifelong embodied agent learning, rather than solving the 3D perception or sensorimotor control problems. VOYAGER is orthogonal and can be combined with gradient-based approaches like VPT [8] as long as the controller provides a code API. We make a system-level comparison between VOYAGER and prior Minecraft agents in Table. A.2.

3.3 Evaluation Results

We systematically evaluate VOYAGER and baselines on their exploration performance, tech tree mastery, map coverage, and zero-shot generalization capability to novel tasks in a new world.

Significantly better exploration. Results of exploration performance are shown in Fig. 1. VOYAGER's superiority is evident in its ability to consistently make new strides, discovering 63 unique items within 160 prompting iterations, 3.3× many novel items compared to its counterparts. On the other hand, AutoGPT lags considerably in discovering new items, while ReAct and Reflexion struggle to make significant progress, given the abstract nature of the open-ended exploration goal that is challenging to execute without an appropriate curriculum.

Consistent tech tree mastery. The Minecraft tech tree tests the agent's ability to craft and use a hierarchy of tools. Progressing through this tree (wooden tool → stone tool → iron tool → diamond tool) requires the agent to master systematic and compositional skills. Compared with baselines, VOYAGER unlocks the wooden level 15.3× faster (in terms of the prompting iterations), the stone level 8.5× faster, the iron level 6.4× faster, and VOYAGER is the only one to unlock the diamond level of the tech tree (Fig. 2 and Table. 1). This underscores the effectiveness of the automatic curriculum, which consistently presents challenges of suitable complexity to facilitate the agent's progress.

Extensive map traversal. VOYAGER is able to navigate distances 2.3× longer compared to baselines by traversing a variety of terrains, while the baseline agents often find themselves confined to local areas, which significantly hampers their capacity to discover new knowledge (Fig. 7).

Efficient zero-shot generalization to unseen tasks. To evaluate zero-shot generalization, we clear the agent's inventory, reset it to a newly instantiated world, and test it with unseen tasks. For both

Table 2: Zero-shot generalization to unseen tasks. Fractions indicate the number of successful trials out of three total attempts. 0/3 means the method fails to solve the task within the maximal prompting iterations (50). Numbers are prompting iterations averaged over three trials. The fewer the iterations, the more efficient the method.

Method	Diamond Pickaxe	Golden Sword	Lava Bucket	Compass
ReAct [29]	N/A (0/3)	N/A (0/3)	N/A (0/3)	N/A (0/3)
Reflexion [30]	N/A (0/3)	N/A (0/3)	N/A (0/3)	N/A (0/3)
AutoGPT [28]	N/A (0/3)	N/A (0/3)	N/A (0/3)	N/A (0/3)
AutoGPT [28] w/ Our Skill Library	39 (1/3)	30 (1/3)	N/A (0/3)	30 (2/3)
VOYAGER w/o Skill Library	36 (2/3)	30 ± 9 (3/3)	27 ± 9 (3/3)	26 ± 3 (3/3)
VOYAGER (Ours)	**19 ± 3** (3/3)	**18 ± 7** (3/3)	**21 ± 5** (3/3)	**18 ± 2** (3/3)

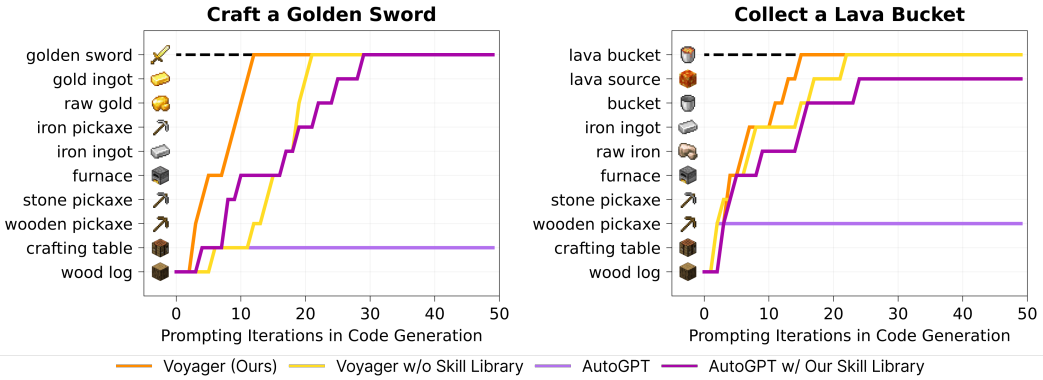

Figure 8: Zero-shot generalization to unseen tasks. We visualize the intermediate progress of each method on two tasks. See Appendix, Sec. B.4.3 for the other two tasks. We do not plot ReAct and Reflexion since they do not make any meaningful progress.

VOYAGER and AutoGPT, we utilize GPT-4 to break down the task into a series of subgoals. Table. 2 and Fig. 8 show VOYAGER can consistently solve all the tasks, while baselines cannot solve any task within 50 prompting iterations. What's interesting to note is that our skill library constructed from lifelong learning not only enhances VOYAGER's performance but also gives a boost to AutoGPT. This demonstrates that the skill library serves as a versatile tool that can be readily employed by other methods, effectively acting as a plug-and-play asset to enhance performance.

3.4 Ablation Studies

We ablate 6 design choices (automatic curriculum, skill library, environment feedback, execution errors, self-verification, and GPT-4 for code generation) in VOYAGER and study their impact on exploration performance (see Appendix, Sec. B.3 for details of each ablated variant). Results are shown in Fig. 9. We highlight a few findings. **The automatic curriculum is crucial for the agent's consistent progress.** The item count drops by 93% if replacing it with a random one since a random curriculum could present tasks that are overly challenging for the agent. On the other hand, a manually designed curriculum ceases once its subgoals are fully accomplished, discovering only 28% of items obtained by our automatic curriculum. **VOYAGER w/o skill library exhibits a tendency to plateau in the later stages.** This underscores the pivotal role that the skill library plays in VOYAGER. It facilitates the formation of increasingly intricate behaviors and consistently nudges the agent's limits by promoting the acquisition of new skills built on top of previously learned ones. Each type of feedback is vital for VOYAGER's ongoing progress. **Of all the feedback types, self-verification is the most critical one**, and removing it leads to a significant drop of 73% in the final item count. **GPT-4 significantly outperforms GPT-3.5 in code generation** and obtains 5.7× many unique items, which corroborates findings from recent studies [56, 57].

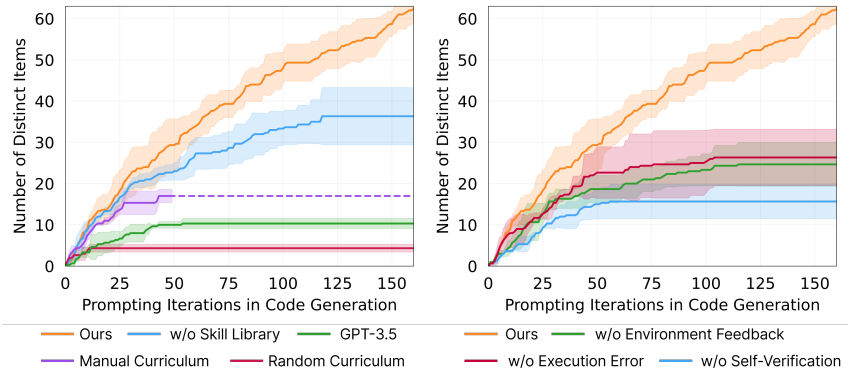

Figure 9: **Left: Ablation studies for the automatic curriculum, skill library, and GPT-4.** GPT-3.5 means replacing GPT-4 with GPT-3.5 for code generation. VOYAGER outperforms all the alternatives, demonstrating the critical role of each component. **Right: Ablation studies for the iterative prompting mechanism.** VOYAGER surpasses all the other options, thereby highlighting the essential significance of each type of feedback in the iterative prompting mechanism.

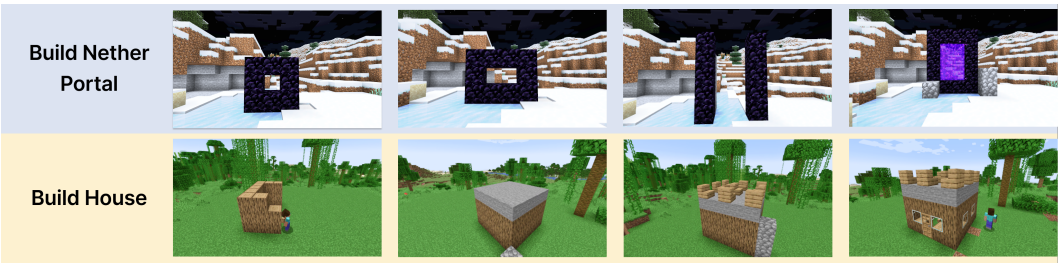

Figure 10: VOYAGER builds 3D structures with human feedback. The progress of building designs that integrate human input is demonstrated from left to right.

4 Limitations and Future Work

Multimodal feedback: VOYAGER does not have visual perception because the current version of GPT-4 is text-based. However, we show that VOYAGER, when aided by human feedback, can construct 3D structures in Minecraft, such as Nether Portal and shelter house (Fig. 10). See Appendix Sec. B.4.4 for human feedback experiment details. This is a proof of concept that a broader scope of tasks can be achieved with more powerful multimodal models [58, 59]. **Cost**: The GPT-4 API incurs significant costs. It is $15\times$ more expensive than GPT-3.5. Nevertheless, VOYAGER is enabled by the quantum leap in code generation quality provided by GPT-4 (Fig. 9) over GPT-3.5 or open-source LLMs [60]. **Inaccuracies**: Despite the iterative prompting mechanism, there are still cases where the agent gets stuck and fails to generate the correct skill. The automatic curriculum has the flexibility to reattempt this task at a later time. Occasionally, self-verification module may also fail, such as not recognizing spider string as a success signal of beating a spider. These limitations provide a roadmap for improvement and we hope to see that additional model fine-tuning will progressively address and overcome these limitations.

5 Related work

Decision-making Agents in Minecraft. Minecraft is an open-ended 3D world with incredibly flexible game mechanics supporting a broad spectrum of activities. Built upon notable Minecraft benchmarks [23, 61–65], Minecraft learning algorithms can be divided into two categories: 1) Low-level controller: Many prior efforts leverage hierarchical reinforcement learning to learn from human demonstrations [66–68]. Kanitscheider et al. [14] design a curriculum based on success rates, but its objectives are limited to curated items. MineDojo [23] and VPT [8] utilize YouTube videos for large-scale pre-training. DreamerV3 [69], on the other hand, learns a world model to explore

the environment and collect diamonds. 2) High-level planner: Volum et al. [70] leverage few-shot prompting with Codex [41] to generate executable policies, but they require additional human interaction. Recent works leverage LLMs as a high-level planner in Minecraft by decomposing a high-level task into several subgoals following Minecraft recipes [55, 53, 71], thus lacking full exploration flexibility. Like these latter works, VOYAGER also uses LLMs as a high-level planner by prompting GPT-4 and utilizes Mineflayer [52] as a low-level controller following Volum et al. [70]. Unlike prior works, VOYAGER employs an automatic curriculum that unfolds in a bottom-up manner, driven by curiosity, and therefore enables open-ended exploration.

Large Language Models for Agent Planning. Inspired by the strong emergent capabilities of LLMs, such as zero-shot prompting and complex reasoning [72, 37, 38, 36, 73, 74], embodied agent research [75–78] has witnessed a significant increase in the utilization of LLMs for planning purposes. Recent efforts can be roughly classified into two groups. 1) Large language models for robot learning: Many prior works apply LLMs to generate subgoals for robot planning [27, 27, 25, 79, 80]. Inner Monologue [26] incorporates environment feedback for robot planning with LLMs. Code as Policies [16] and ProgPrompt [22] directly leverage LLMs to generate executable robot policies. VIMA [19] and PaLM-E [58] fine-tune pre-trained LLMs to support multimodal prompts. 2) Large language models for text agents: ReAct [29] leverages chain-of-thought prompting [46] and generates both reasoning traces and task-specific actions with LLMs. Reflexion [30] is built upon ReAct [29] with self-reflection to enhance reasoning. AutoGPT [28] is a popular tool that automates NLP tasks by crafting a curriculum of multiple subgoals for completing a high-level goal while incorporating ReAct [29]'s reasoning and acting loops. DERA [81] frames a task as a dialogue between two GPT-4 [35] agents. Generative Agents [82] leverages ChatGPT [50] to simulate human behaviors by storing agents' experiences as memories and retrieving those for planning, but its agent actions are not executable. SPRING [83] is a concurrent work that uses GPT-4 to extract game mechanics from game manuals, based on which it answers questions arranged in a directed acyclic graph and predicts the next action. All these works lack a skill library for developing more complex behaviors, which are crucial components for the success of VOYAGER in lifelong learning.

Code Generation with Execution. Code generation has been a longstanding challenge in NLP [41, 84, 85, 73, 37], with various works leveraging execution results to improve program synthesis. Execution-guided approaches leverage intermediate execution outcomes to guide program search [86–88]. Another line of research utilizes majority voting to choose candidates based on their execution performance [89, 90]. Additionally, LEVER [91] trains a verifier to distinguish and reject incorrect programs based on execution results. CLAIRIFY [92], on the other hand, generates code for planning chemistry experiments and makes use of a rule-based verifier to iteratively provide error feedback to LLMs. VOYAGER distinguishes itself from these works by integrating environment feedback, execution errors, and self-verification (to assess task success) into an iterative prompting mechanism for embodied control.

6 Conclusion

In this work, we introduce VOYAGER, the first LLM-powered embodied lifelong learning agent, which leverages GPT-4 to explore the world continuously, develop increasingly sophisticated skills, and make new discoveries consistently without human intervention. VOYAGER exhibits superior performance in discovering novel items, unlocking the Minecraft tech tree, traversing diverse terrains, and applying its learned skill library to unseen tasks in a newly instantiated world. VOYAGER serves as a starting point to develop powerful generalist agents without tuning the model parameters.

7 Acknowledgements

We are extremely grateful to Ziming Zhu, Kaiyu Yang, Rafał Kocielnik, Colin White, Or Sharir, Sahin Lale, De-An Huang, Jean Kossaifi, Yuncong Yang, Charles Zhang, Minchao Huang, and many other colleagues and friends for their helpful feedback and insightful discussions. This work is done during Guanzhi Wang's internship at NVIDIA. Guanzhi Wang is supported by the Kortschak fellowship in Computing and Mathematical Sciences at Caltech.

References

[1] Eric Kolve, Roozbeh Mottaghi, Winson Han, Eli VanderBilt, Luca Weihs, Alvaro Herrasti, Daniel Gordon, Yuke Zhu, Abhinav Gupta, and Ali Farhadi. Ai2-thor: An interactive 3d environment for visual ai. *arXiv preprint arXiv: Arxiv-1712.05474*, 2017.

[2] Manolis Savva, Jitendra Malik, Devi Parikh, Dhruv Batra, Abhishek Kadian, Oleksandr Maksymets, Yili Zhao, Erik Wijmans, Bhavana Jain, Julian Straub, Jia Liu, and Vladlen Koltun. Habitat: A platform for embodied AI research. In *2019 IEEE/CVF International Conference on Computer Vision, ICCV 2019, Seoul, Korea (South), October 27 - November 2, 2019*, pages 9338–9346. IEEE, 2019.

[3] Yuke Zhu, Josiah Wong, Ajay Mandlekar, and Roberto Martín-Martín. robosuite: A modular simulation framework and benchmark for robot learning. *arXiv preprint arXiv: Arxiv-2009.12293*, 2020.

[4] Fei Xia, William B. Shen, Chengshu Li, Priya Kasimbeg, Micael Tchapmi, Alexander Toshev, Li Fei-Fei, Roberto Martín-Martín, and Silvio Savarese. Interactive gibson benchmark (igibson 0.5): A benchmark for interactive navigation in cluttered environments. *arXiv preprint arXiv: Arxiv-1910.14442*, 2019.

[5] Bokui Shen, Fei Xia, Chengshu Li, Roberto Martín-Martín, Linxi Fan, Guanzhi Wang, Claudia Pérez-D'Arpino, Shyamal Buch, Sanjana Srivastava, Lyne P. Tchapmi, Micael E. Tchapmi, Kent Vainio, Josiah Wong, Li Fei-Fei, and Silvio Savarese. igibson 1.0: a simulation environment for interactive tasks in large realistic scenes. *arXiv preprint arXiv: Arxiv-2012.02924*, 2020.

[6] Jens Kober, J Andrew Bagnell, and Jan Peters. Reinforcement learning in robotics: A survey. *The International Journal of Robotics Research*, 32(11):1238–1274, 2013.

[7] Kai Arulkumaran, Marc Peter Deisenroth, Miles Brundage, and Anil Anthony Bharath. Deep reinforcement learning: A brief survey. *IEEE Signal Processing Magazine*, 34(6):26–38, 2017.

[8] Bowen Baker, Ilge Akkaya, Peter Zhokhov, Joost Huizinga, Jie Tang, Adrien Ecoffet, Brandon Houghton, Raul Sampedro, and Jeff Clune. Video pretraining (vpt): Learning to act by watching unlabeled online videos. *arXiv preprint arXiv: Arxiv-2206.11795*, 2022.

[9] DeepMind Interactive Agents Team, Josh Abramson, Arun Ahuja, Arthur Brussee, Federico Carnevale, Mary Cassin, Felix Fischer, Petko Georgiev, Alex Goldin, Mansi Gupta, Tim Harley, Felix Hill, Peter C Humphreys, Alden Hung, Jessica Landon, Timothy Lillicrap, Hamza Merzic, Alistair Muldal, Adam Santoro, Guy Scully, Tamara von Glehn, Greg Wayne, Nathaniel Wong, Chen Yan, and Rui Zhu. Creating multimodal interactive agents with imitation and self-supervised learning. *arXiv preprint arXiv: Arxiv-2112.03763*, 2021.

[10] Oriol Vinyals, Igor Babuschkin, Junyoung Chung, Michael Mathieu, Max Jaderberg, Wojciech M Czarnecki, Andrew Dudzik, Aja Huang, Petko Georgiev, Richard Powell, et al. Alphastar: Mastering the real-time strategy game starcraft ii. *DeepMind blog*, 2, 2019.

[11] Adrien Ecoffet, Joost Huizinga, Joel Lehman, Kenneth O. Stanley, and Jeff Clune. Go-explore: a new approach for hard-exploration problems. *arXiv preprint arXiv: Arxiv-1901.10995*, 2019.

[12] Joost Huizinga and Jeff Clune. Evolving multimodal robot behavior via many stepping stones with the combinatorial multiobjective evolutionary algorithm. *Evolutionary computation*, 30(2):131–164, 2022.

[13] Rui Wang, Joel Lehman, Aditya Rawal, Jiale Zhi, Yulun Li, Jeffrey Clune, and Kenneth O. Stanley. Enhanced POET: open-ended reinforcement learning through unbounded invention of learning challenges and their solutions. In *Proceedings of the 37th International Conference on Machine Learning, ICML 2020, 13-18 July 2020, Virtual Event*, volume 119 of *Proceedings of Machine Learning Research*, pages 9940–9951. PMLR, 2020.

[14] Ingmar Kanitscheider, Joost Huizinga, David Farhi, William Hebgen Guss, Brandon Houghton, Raul Sampedro, Peter Zhokhov, Bowen Baker, Adrien Ecoffet, Jie Tang, Oleg Klimov, and Jeff Clune. Multi-task curriculum learning in a complex, visual, hard-exploration domain: Minecraft. *arXiv preprint arXiv: Arxiv-2106.14876*, 2021.

[15] Michael Dennis, Natasha Jaques, Eugene Vinitsky, Alexandre M. Bayen, Stuart Russell, Andrew Critch, and Sergey Levine. Emergent complexity and zero-shot transfer via unsupervised environment design. In Hugo Larochelle, Marc'Aurelio Ranzato, Raia Hadsell, Maria-Florina Balcan, and Hsuan-Tien Lin, editors, *Advances in Neural Information Processing Systems 33: Annual Conference on Neural Information Processing Systems 2020, NeurIPS 2020, December 6-12, 2020, virtual*, 2020.

[16] Jacky Liang, Wenlong Huang, Fei Xia, Peng Xu, Karol Hausman, Brian Ichter, Pete Florence, and Andy Zeng. Code as policies: Language model programs for embodied control. *arXiv preprint arXiv: Arxiv-2209.07753*, 2022.

[17] Shao-Hua Sun, Te-Lin Wu, and Joseph J. Lim. Program guided agent. In *8th International Conference on Learning Representations, ICLR 2020, Addis Ababa, Ethiopia, April 26-30, 2020*. OpenReview.net, 2020.

[18] Zelin Zhao, Karan Samel, Binghong Chen, and Le Song. Proto: Program-guided transformer for program-guided tasks. In Marc'Aurelio Ranzato, Alina Beygelzimer, Yann N. Dauphin, Percy Liang, and Jennifer Wortman Vaughan, editors, *Advances in Neural Information Processing Systems 34: Annual Conference on Neural Information Processing Systems 2021, NeurIPS 2021, December 6-14, 2021, virtual*, pages 17021–17036, 2021.

[19] Yunfan Jiang, Agrim Gupta, Zichen Zhang, Guanzhi Wang, Yongqiang Dou, Yanjun Chen, Li Fei-Fei, Anima Anandkumar, Yuke Zhu, and Linxi (Jim) Fan. Vima: General robot manipulation with multimodal prompts. *ARXIV.ORG*, 2022.

[20] Mohit Shridhar, Lucas Manuelli, and Dieter Fox. Cliport: What and where pathways for robotic manipulation. *arXiv preprint arXiv: Arxiv-2109.12098*, 2021.

[21] Linxi Fan, Guanzhi Wang, De-An Huang, Zhiding Yu, Li Fei-Fei, Yuke Zhu, and Animashree Anandkumar. SECANT: self-expert cloning for zero-shot generalization of visual policies. In Marina Meila and Tong Zhang, editors, *Proceedings of the 38th International Conference on Machine Learning, ICML 2021, 18-24 July 2021, Virtual Event*, volume 139 of *Proceedings of Machine Learning Research*, pages 3088–3099. PMLR, 2021.

[22] Ishika Singh, Valts Blukis, Arsalan Mousavian, Ankit Goyal, Danfei Xu, Jonathan Tremblay, Dieter Fox, Jesse Thomason, and Animesh Garg. Progprompt: Generating situated robot task plans using large language models. *arXiv preprint arXiv: Arxiv-2209.11302*, 2022.

[23] Linxi Fan, Guanzhi Wang, Yunfan Jiang, Ajay Mandlekar, Yuncong Yang, Haoyi Zhu, Andrew Tang, De-An Huang, Yuke Zhu, and Anima Anandkumar. Minedojo: Building open-ended embodied agents with internet-scale knowledge. *arXiv preprint arXiv: Arxiv-2206.08853*, 2022.

[24] Andy Zeng, Adrian Wong, Stefan Welker, Krzysztof Choromanski, Federico Tombari, Aveek Purohit, Michael Ryoo, Vikas Sindhwani, Johnny Lee, Vincent Vanhoucke, and Pete Florence. Socratic models: Composing zero-shot multimodal reasoning with language. *arXiv preprint arXiv: Arxiv-2204.00598*, 2022.

[25] Michael Ahn, Anthony Brohan, Noah Brown, Yevgen Chebotar, Omar Cortes, Byron David, Chelsea Finn, Keerthana Gopalakrishnan, Karol Hausman, Alex Herzog, Daniel Ho, Jasmine Hsu, Julian Ibarz, Brian Ichter, Alex Irpan, Eric Jang, Rosario Jauregui Ruano, Kyle Jeffrey, Sally Jesmonth, Nikhil J Joshi, Ryan Julian, Dmitry Kalashnikov, Yuheng Kuang, Kuang-Huei Lee, Sergey Levine, Yao Lu, Linda Luu, Carolina Parada, Peter Pastor, Jornell Quiambao, Kanishka Rao, Jarek Rettinghouse, Diego Reyes, Pierre Sermanet, Nicolas Sievers, Clayton Tan, Alexander Toshev, Vincent Vanhoucke, Fei Xia, Ted Xiao, Peng Xu, Sichun Xu, and Mengyuan Yan. Do as i can, not as i say: Grounding language in robotic affordances. *arXiv preprint arXiv: Arxiv-2204.01691*, 2022.

[26] Wenlong Huang, Fei Xia, Ted Xiao, Harris Chan, Jacky Liang, Pete Florence, Andy Zeng, Jonathan Tompson, Igor Mordatch, Yevgen Chebotar, Pierre Sermanet, Noah Brown, Tomas Jackson, Linda Luu, Sergey Levine, Karol Hausman, and Brian Ichter. Inner monologue: Embodied reasoning through planning with language models. *arXiv preprint arXiv: Arxiv-2207.05608*, 2022.

[27] Wenlong Huang, Pieter Abbeel, Deepak Pathak, and Igor Mordatch. Language models as zero-shot planners: Extracting actionable knowledge for embodied agents. In Kamalika Chaudhuri, Stefanie Jegelka, Le Song, Csaba Szepesvári, Gang Niu, and Sivan Sabato, editors, *International Conference on Machine Learning, ICML 2022, 17-23 July 2022, Baltimore, Maryland, USA*, volume 162 of *Proceedings of Machine Learning Research*, pages 9118–9147. PMLR, 2022.

[28] Significant-gravitas/auto-gpt: An experimental open-source attempt to make gpt-4 fully autonomous., 2023.

[29] Shunyu Yao, Jeffrey Zhao, Dian Yu, Nan Du, Izhak Shafran, Karthik Narasimhan, and Yuan Cao. React: Synergizing reasoning and acting in language models. *arXiv preprint arXiv: Arxiv-2210.03629*, 2022.

[30] Noah Shinn, Beck Labash, and Ashwin Gopinath. Reflexion: an autonomous agent with dynamic memory and self-reflection. *arXiv preprint arXiv: Arxiv-2303.11366*, 2023.

[31] German Ignacio Parisi, Ronald Kemker, Jose L. Part, Christopher Kanan, and Stefan Wermter. Continual lifelong learning with neural networks: A review. *Neural Networks*, 113:54–71, 2019.

[32] Liyuan Wang, Xingxing Zhang, Hang Su, and Jun Zhu. A comprehensive survey of continual learning: Theory, method and application. *arXiv preprint arXiv: Arxiv-2302.00487*, 2023.

[33] Volodymyr Mnih, Koray Kavukcuoglu, David Silver, Alex Graves, Ioannis Antonoglou, Daan Wierstra, and Martin Riedmiller. Playing atari with deep reinforcement learning. *arXiv preprint arXiv: Arxiv-1312.5602*, 2013.

[34] OpenAI, :, Christopher Berner, Greg Brockman, Brooke Chan, Vicki Cheung, Przemysław Dębiak, Christy Dennison, David Farhi, Quirin Fischer, Shariq Hashme, Chris Hesse, Rafal Józefowicz, Scott Gray, Catherine Olsson, Jakub Pachocki, Michael Petrov, Henrique P. d. O. Pinto, Jonathan Raiman, Tim Salimans, Jeremy Schlatter, Jonas Schneider, Szymon Sidor, Ilya Sutskever, Jie Tang, Filip Wolski, and Susan Zhang. Dota 2 with large scale deep reinforcement learning. *arXiv preprint arXiv: Arxiv-1912.06680*, 2019.

[35] OpenAI. Gpt-4 technical report. *arXiv preprint arXiv: Arxiv-2303.08774*, 2023.

[36] Jason Wei, Yi Tay, Rishi Bommasani, Colin Raffel, Barret Zoph, Sebastian Borgeaud, Dani Yogatama, Maarten Bosma, Denny Zhou, Donald Metzler, Ed H. Chi, Tatsunori Hashimoto, Oriol Vinyals, Percy Liang, Jeff Dean, and William Fedus. Emergent abilities of large language models. *arXiv preprint arXiv: Arxiv-2206.07682*, 2022.

[37] Tom B. Brown, Benjamin Mann, Nick Ryder, Melanie Subbiah, Jared Kaplan, Prafulla Dhariwal, Arvind Neelakantan, Pranav Shyam, Girish Sastry, Amanda Askell, Sandhini Agarwal, Ariel Herbert-Voss, Gretchen Krueger, Tom Henighan, Rewon Child, Aditya Ramesh, Daniel M. Ziegler, Jeffrey Wu, Clemens Winter, Christopher Hesse, Mark Chen, Eric Sigler, Mateusz Litwin, Scott Gray, Benjamin Chess, Jack Clark, Christopher Berner, Sam McCandlish, Alec Radford, Ilya Sutskever, and Dario Amodei. Language models are few-shot learners. In Hugo Larochelle, Marc'Aurelio Ranzato, Raia Hadsell, Maria-Florina Balcan, and Hsuan-Tien Lin, editors, *Advances in Neural Information Processing Systems 33: Annual Conference on Neural Information Processing Systems 2020, NeurIPS 2020, December 6-12, 2020, virtual*, 2020.

[38] Colin Raffel, Noam Shazeer, Adam Roberts, Katherine Lee, Sharan Narang, Michael Matena, Yanqi Zhou, Wei Li, and Peter J. Liu. Exploring the limits of transfer learning with a unified text-to-text transformer. *J. Mach. Learn. Res.*, 21:140:1–140:67, 2020.

[39] Benjamin Eysenbach, Abhishek Gupta, Julian Ibarz, and Sergey Levine. Diversity is all you need: Learning skills without a reward function. In *7th International Conference on Learning Representations, ICLR 2019, New Orleans, LA, USA, May 6-9, 2019*. OpenReview.net, 2019.

[40] Edoardo Conti, Vashisht Madhavan, Felipe Petroski Such, Joel Lehman, Kenneth O. Stanley, and Jeff Clune. Improving exploration in evolution strategies for deep reinforcement learning via a population of novelty-seeking agents. In Samy Bengio, Hanna M. Wallach, Hugo Larochelle, Kristen Grauman, Nicolò Cesa-Bianchi, and Roman Garnett, editors, *Advances in Neural Information Processing Systems 31: Annual Conference on Neural Information Processing Systems 2018, NeurIPS 2018, December 3-8, 2018, Montréal, Canada*, pages 5032–5043, 2018.

[41] Mark Chen, Jerry Tworek, Heewoo Jun, Qiming Yuan, Henrique Ponde de Oliveira Pinto, Jared Kaplan, Harri Edwards, Yuri Burda, Nicholas Joseph, Greg Brockman, Alex Ray, Raul Puri, Gretchen Krueger, Michael Petrov, Heidy Khlaaf, Girish Sastry, Pamela Mishkin, Brooke Chan, Scott Gray, Nick Ryder, Mikhail Pavlov, Alethea Power, Lukasz Kaiser, Mohammad Bavarian, Clemens Winter, Philippe Tillet, Felipe Petroski Such, Dave Cummings, Matthias Plappert, Fotios Chantzis, Elizabeth Barnes, Ariel Herbert-Voss, William Hebgen Guss, Alex Nichol, Alex Paino, Nikolas Tezak, Jie Tang, Igor Babuschkin, Suchir Balaji, Shantanu Jain, William Saunders, Christopher Hesse, Andrew N. Carr, Jan Leike, Josh Achiam, Vedant Misra, Evan Morikawa, Alec Radford, Matthew Knight, Miles Brundage, Mira Murati, Katie Mayer, Peter Welinder, Bob McGrew, Dario Amodei, Sam McCandlish, Ilya Sutskever, and Wojciech Zaremba. Evaluating large language models trained on code. *arXiv preprint arXiv: Arxiv-2107.03374*, 2021.

[42] Rui Wang, Joel Lehman, Jeff Clune, and Kenneth O. Stanley. Paired open-ended trailblazer (poet): Endlessly generating increasingly complex and diverse learning environments and their solutions. *arXiv preprint arXiv: Arxiv-1901.01753*, 2019.

[43] Rémy Portelas, Cédric Colas, Lilian Weng, Katja Hofmann, and Pierre-Yves Oudeyer. Automatic curriculum learning for deep RL: A short survey. In Christian Bessiere, editor, *Proceedings of the Twenty-Ninth International Joint Conference on Artificial Intelligence, IJCAI 2020*, pages 4819–4825. ijcai.org, 2020.

[44] Sébastien Forestier, Rémy Portelas, Yoan Mollard, and Pierre-Yves Oudeyer. Intrinsically motivated goal exploration processes with automatic curriculum learning. *The Journal of Machine Learning Research*, 23(1):6818–6858, 2022.

[45] Kevin Ellis, Catherine Wong, Maxwell Nye, Mathias Sable-Meyer, Luc Cary, Lucas Morales, Luke Hewitt, Armando Solar-Lezama, and Joshua B. Tenenbaum. Dreamcoder: Growing generalizable, interpretable knowledge with wake-sleep bayesian program learning. *arXiv preprint arXiv: Arxiv-2006.08381*, 2020.

[46] Jason Wei, Xuezhi Wang, Dale Schuurmans, Maarten Bosma, Ed Chi, Quoc Le, and Denny Zhou. Chain of thought prompting elicits reasoning in large language models. *arXiv preprint arXiv: Arxiv-2201.11903*, 2022.

[47] Volodymyr Mnih, Adrià Puigdomènech Badia, Mehdi Mirza, Alex Graves, Timothy P. Lillicrap, Tim Harley, David Silver, and Koray Kavukcuoglu. Asynchronous methods for deep reinforcement learning. In Maria-Florina Balcan and Kilian Q. Weinberger, editors, *Proceedings of the 33nd International Conference on Machine Learning, ICML 2016, New York City, NY, USA, June 19-24, 2016*, volume 48 of *JMLR Workshop and Conference Proceedings*, pages 1928–1937. JMLR.org, 2016.

[48] John Schulman, Filip Wolski, Prafulla Dhariwal, Alec Radford, and Oleg Klimov. Proximal policy optimization algorithms. *arXiv preprint arXiv: Arxiv-1707.06347*, 2017.

[49] Timothy P. Lillicrap, Jonathan J. Hunt, Alexander Pritzel, Nicolas Heess, Tom Erez, Yuval Tassa, David Silver, and Daan Wierstra. Continuous control with deep reinforcement learning. In Yoshua Bengio and Yann LeCun, editors, *4th International Conference on Learning Representations, ICLR 2016, San Juan, Puerto Rico, May 2-4, 2016, Conference Track Proceedings*, 2016.

[50] Introducing chatgpt, 2022.

[51] New and improved embedding model, 2022.

[52] PrismarineJS. Prismarinejs/mineflayer: Create minecraft bots with a powerful, stable, and high level javascript api., 2013.

[53] Kolby Nottingham, Prithviraj Ammanabrolu, Alane Suhr, Yejin Choi, Hanna Hajishirzi, Sameer Singh, and Roy Fox. Do embodied agents dream of pixelated sheep?: Embodied decision making using language guided world modelling. *ARXIV.ORG*, 2023.

[54] Shaofei Cai, Zihao Wang, Xiaojian Ma, Anji Liu, and Yitao Liang. Open-world multi-task control through goal-aware representation learning and adaptive horizon prediction. *arXiv preprint arXiv: Arxiv-2301.10034*, 2023.

[55] Zihao Wang, Shaofei Cai, Anji Liu, Xiaojian Ma, and Yitao Liang. Describe, explain, plan and select: Interactive planning with large language models enables open-world multi-task agents. *arXiv preprint arXiv: Arxiv-2302.01560*, 2023.

[56] Sébastien Bubeck, Varun Chandrasekaran, Ronen Eldan, Johannes Gehrke, Eric Horvitz, Ece Kamar, Peter Lee, Yin Tat Lee, Yuanzhi Li, Scott Lundberg, Harsha Nori, Hamid Palangi, Marco Tulio Ribeiro, and Yi Zhang. Sparks of artificial general intelligence: Early experiments with gpt-4. *arXiv preprint arXiv: Arxiv-2303.12712*, 2023.

[57] Yiheng Liu, Tianle Han, Siyuan Ma, Jiayue Zhang, Yuanyuan Yang, Jiaming Tian, Hao He, Antong Li, Mengshen He, Zhengliang Liu, Zihao Wu, Dajiang Zhu, Xiang Li, Ning Qiang, Dingang Shen, Tianming Liu, and Bao Ge. Summary of chatgpt/gpt-4 research and perspective towards the future of large language models. *arXiv preprint arXiv: Arxiv-2304.01852*, 2023.

[58] Danny Driess, Fei Xia, Mehdi S. M. Sajjadi, Corey Lynch, Aakanksha Chowdhery, Brian Ichter, Ayzaan Wahid, Jonathan Tompson, Quan Vuong, Tianhe Yu, Wenlong Huang, Yevgen Chebotar, Pierre Sermanet, Daniel Duckworth, Sergey Levine, Vincent Vanhoucke, Karol Hausman, Marc Toussaint, Klaus Greff, Andy Zeng, Igor Mordatch, and Pete Florence. Palm-e: An embodied multimodal language model. *arXiv preprint arXiv: Arxiv-2303.03378*, 2023.

[59] Shikun Liu, Linxi Fan, Edward Johns, Zhiding Yu, Chaowei Xiao, and Anima Anandkumar. Prismer: A vision-language model with an ensemble of experts. *arXiv preprint arXiv: Arxiv-2303.02506*, 2023.

[60] Hugo Touvron, Thibaut Lavril, Gautier Izacard, Xavier Martinet, Marie-Anne Lachaux, Timothée Lacroix, Baptiste Rozière, Naman Goyal, Eric Hambro, Faisal Azhar, Aurelien Rodriguez, Armand Joulin, Edouard Grave, and Guillaume Lample. Llama: Open and efficient foundation language models. *arXiv preprint arXiv: Arxiv-2302.13971*, 2023.

[61] William H. Guss, Brandon Houghton, Nicholay Topin, Phillip Wang, Cayden Codel, Manuela Veloso, and Ruslan Salakhutdinov. Minerl: A large-scale dataset of minecraft demonstrations. In Sarit Kraus, editor, *Proceedings of the Twenty-Eighth International Joint Conference on Artificial Intelligence, IJCAI 2019, Macao, China, August 10-16, 2019*, pages 2442–2448. ijcai.org, 2019.

[62] William H. Guss, Cayden Codel, Katja Hofmann, Brandon Houghton, Noboru Kuno, Stephanie Milani, Sharada Mohanty, Diego Perez Liebana, Ruslan Salakhutdinov, Nicholay Topin, Manuela Veloso, and Phillip Wang. The minerl 2019 competition on sample efficient reinforcement learning using human priors. *arXiv preprint arXiv: Arxiv-1904.10079*, 2019.

[63] William H. Guss, Mario Ynocente Castro, Sam Devlin, Brandon Houghton, Noboru Sean Kuno, Crissman Loomis, Stephanie Milani, Sharada Mohanty, Keisuke Nakata, Ruslan Salakhutdinov, John Schulman, Shinya Shiroshita, Nicholay Topin, Avinash Ummadisingu, and Oriol Vinyals. The minerl 2020 competition on sample efficient reinforcement learning using human priors. *arXiv preprint arXiv: Arxiv-2101.11071*, 2021.

[64] Anssi Kanervisto, Stephanie Milani, Karolis Ramanauskas, Nicholay Topin, Zichuan Lin, Junyou Li, Jianing Shi, Deheng Ye, Qiang Fu, Wei Yang, Weijun Hong, Zhongyue Huang, Haicheng Chen, Guangjun Zeng, Yue Lin, Vincent Micheli, Eloi Alonso, François Fleuret, Alexander Nikulin, Yury Belousov, Oleg Svidchenko, and Aleksei Shpilman. Minerl diamond 2021 competition: Overview, results, and lessons learned. *arXiv preprint arXiv: Arxiv-2202.10583*, 2022.

[65] Matthew Johnson, Katja Hofmann, Tim Hutton, and David Bignell. The malmo platform for artificial intelligence experimentation. In Subbarao Kambhampati, editor, *Proceedings of the Twenty-Fifth International Joint Conference on Artificial Intelligence, IJCAI 2016, New York, NY, USA, 9-15 July 2016*, pages 4246–4247. IJCAI/AAAI Press, 2016.

[66] Zichuan Lin, Junyou Li, Jianing Shi, Deheng Ye, Qiang Fu, and Wei Yang. Juewu-mc: Playing minecraft with sample-efficient hierarchical reinforcement learning. *arXiv preprint arXiv: Arxiv-2112.04907*, 2021.

[67] Hangyu Mao, Chao Wang, Xiaotian Hao, Yihuan Mao, Yiming Lu, Chengjie Wu, Jianye Hao, Dong Li, and Pingzhong Tang. Seihai: A sample-efficient hierarchical ai for the minerl competition. *arXiv preprint arXiv: Arxiv-2111.08857*, 2021.

[68] Alexey Skrynnik, Aleksey Staroverov, Ermek Aitygulov, Kirill Aksenov, Vasilii Davydov, and Aleksandr I. Panov. Hierarchical deep q-network from imperfect demonstrations in minecraft. *Cogn. Syst. Res.*, 65:74–78, 2021.

[69] Danijar Hafner, Jurgis Pasukonis, Jimmy Ba, and Timothy Lillicrap. Mastering diverse domains through world models. *arXiv preprint arXiv: Arxiv-2301.04104*, 2023.

[70] Ryan Volum, Sudha Rao, Michael Xu, Gabriel DesGarennes, Chris Brockett, Benjamin Van Durme, Olivia Deng, Akanksha Malhotra, and Bill Dolan. Craft an iron sword: Dynamically generating interactive game characters by prompting large language models tuned on code. In *Proceedings of the 3rd Wordplay: When Language Meets Games Workshop (Wordplay 2022)*, pages 25–43, Seattle, United States, 2022. Association for Computational Linguistics.

[71] Haoqi Yuan, Chi Zhang, Hongcheng Wang, Feiyang Xie, Penglin Cai, Hao Dong, and Zongqing Lu. Plan4mc: Skill reinforcement learning and planning for open-world minecraft tasks. *arXiv preprint arXiv: 2303.16563*, 2023.

[72] Rishi Bommasani, Drew A. Hudson, Ehsan Adeli, Russ Altman, Simran Arora, Sydney von Arx, Michael S. Bernstein, Jeannette Bohg, Antoine Bosselut, Emma Brunskill, Erik Brynjolfsson, Shyamal Buch, Dallas Card, Rodrigo Castellon, Niladri Chatterji, Annie Chen, Kathleen Creel, Jared Quincy Davis, Dora Demszky, Chris Donahue, Moussa Doumbouya, Esin Durmus, Stefano Ermon, John Etchemendy, Kawin Ethayarajh, Li Fei-Fei, Chelsea Finn, Trevor Gale, Lauren Gillespie, Karan Goel, Noah Goodman, Shelby Grossman, Neel Guha, Tatsunori Hashimoto, Peter Henderson, John Hewitt, Daniel E. Ho, Jenny Hong, Kyle Hsu, Jing Huang, Thomas Icard, Saahil Jain, Dan Jurafsky, Pratyusha Kalluri, Siddharth Karamcheti, Geoff Keeling, Fereshte Khani, Omar Khattab, Pang Wei Koh, Mark Krass, Ranjay Krishna, Rohith Kuditipudi, Ananya Kumar, Faisal Ladhak, Mina Lee, Tony Lee, Jure Leskovec, Isabelle Levent, Xiang Lisa Li, Xuechen Li, Tengyu Ma, Ali Malik, Christopher D. Manning, Suvir Mirchandani, Eric Mitchell, Zanele Munyikwa, Suraj Nair, Avanika Narayan, Deepak Narayanan, Ben Newman, Allen Nie, Juan Carlos Niebles, Hamed Nilforoshan, Julian Nyarko, Giray Ogut, Laurel Orr, Isabel Papadimitriou, Joon Sung Park, Chris Piech, Eva Portelance, Christopher Potts, Aditi Raghunathan, Rob Reich, Hongyu Ren, Frieda Rong, Yusuf Roohani, Camilo Ruiz, Jack Ryan, Christopher Ré, Dorsa Sadigh, Shiori Sagawa, Keshav Santhanam, Andy Shih, Krishnan Srinivasan, Alex Tamkin, Rohan Taori, Armin W. Thomas, Florian Tramèr, Rose E. Wang, William Wang, Bohan Wu, Jiajun Wu, Yuhuai Wu, Sang Michael Xie, Michihiro Yasunaga, Jiaxuan You, Matei Zaharia, Michael Zhang, Tianyi Zhang, Xikun Zhang, Yuhui Zhang, Lucia Zheng, Kaitlyn Zhou, and Percy Liang. On the opportunities and risks of foundation models. *arXiv preprint arXiv: Arxiv-2108.07258*, 2021.

[73] Aakanksha Chowdhery, Sharan Narang, Jacob Devlin, Maarten Bosma, Gaurav Mishra, Adam Roberts, Paul Barham, Hyung Won Chung, Charles Sutton, Sebastian Gehrmann, Parker Schuh, Kensen Shi, Sasha Tsvyashchenko, Joshua Maynez, Abhishek Rao, Parker Barnes, Yi Tay, Noam Shazeer, Vinodkumar Prabhakaran, Emily Reif, Nan Du, Ben Hutchinson, Reiner Pope, James Bradbury, Jacob Austin, Michael Isard, Guy Gur-Ari, Pengcheng Yin, Toju Duke, Anselm Levskaya, Sanjay Ghemawat, Sunipa Dev, Henryk Michalewski, Xavier Garcia, Vedant Misra, Kevin Robinson, Liam Fedus, Denny Zhou, Daphne Ippolito, David Luan, Hyeontaek Lim, Barret Zoph, Alexander Spiridonov, Ryan Sepassi, David Dohan, Shivani Agrawal, Mark Omernick, Andrew M. Dai, Thanumalayan Sankaranarayana Pillai, Marie Pellat, Aitor Lewkowycz, Erica Moreira, Rewon Child, Oleksandr Polozov, Katherine Lee, Zongwei Zhou, Xuezhi Wang, Brennan Saeta, Mark Diaz, Orhan Firat, Michele Catasta, Jason Wei, Kathy Meier-Hellstern, Douglas Eck, Jeff Dean, Slav Petrov, and Noah Fiedel. Palm: Scaling language modeling with pathways. *arXiv preprint arXiv: Arxiv-2204.02311*, 2022.

[74] Hyung Won Chung, Le Hou, Shayne Longpre, Barret Zoph, Yi Tay, William Fedus, Eric Li, Xuezhi Wang, Mostafa Dehghani, Siddhartha Brahma, Albert Webson, Shixiang Shane Gu, Zhuyun Dai, Mirac Suzgun, Xinyun Chen, Aakanksha Chowdhery, Sharan Narang, Gaurav Mishra, Adams Yu, Vincent Zhao, Yanping Huang, Andrew Dai, Hongkun Yu, Slav Petrov, Ed H. Chi, Jeff Dean, Jacob Devlin, Adam Roberts, Denny Zhou, Quoc V. Le, and Jason Wei. Scaling instruction-finetuned language models. *arXiv preprint arXiv: Arxiv-2210.11416*, 2022.

[75] Jiafei Duan, Samson Yu, Hui Li Tan, Hongyuan Zhu, and Cheston Tan. A survey of embodied AI: from simulators to research tasks. *IEEE Trans. Emerg. Top. Comput. Intell.*, 6(2):230–244, 2022.

[76] Dhruv Batra, Angel X. Chang, Sonia Chernova, Andrew J. Davison, Jia Deng, Vladlen Koltun, Sergey Levine, Jitendra Malik, Igor Mordatch, Roozbeh Mottaghi, Manolis Savva, and Hao Su. Rearrangement: A challenge for embodied ai. *arXiv preprint arXiv: Arxiv-2011.01975*, 2020.

[77] Harish Ravichandar, Athanasios S Polydoros, Sonia Chernova, and Aude Billard. Recent advances in robot learning from demonstration. *Annual review of control, robotics, and autonomous systems*, 3:297–330, 2020.

[78] Jack Collins, Shelvin Chand, Anthony Vanderkop, and David Howard. A review of physics simulators for robotic applications. *IEEE Access*, 9:51416–51431, 2021.

[79] So Yeon Min, Devendra Singh Chaplot, Pradeep Ravikumar, Yonatan Bisk, and R. Salakhutdinov. Film: Following instructions in language with modular methods. *International Conference on Learning Representations*, 2021.

[80] Valts Blukis, Chris Paxton, Dieter Fox, Animesh Garg, and Yoav Artzi. A persistent spatial semantic representation for high-level natural language instruction execution. In *5th Annual Conference on Robot Learning*, 2021.

[81] Varun Nair, Elliot Schumacher, Geoffrey Tso, and Anitha Kannan. Dera: Enhancing large language model completions with dialog-enabled resolving agents. *arXiv preprint arXiv: Arxiv-2303.17071*, 2023.

[82] Joon Sung Park, Joseph C. O'Brien, Carrie J. Cai, Meredith Ringel Morris, Percy Liang, and Michael S. Bernstein. Generative agents: Interactive simulacra of human behavior. *arXiv preprint arXiv: Arxiv-2304.03442*, 2023.

[83] Yue Wu, Shrimai Prabhumoye, So Yeon Min, Yonatan Bisk, Ruslan Salakhutdinov, Amos Azaria, Tom Mitchell, and Yuanzhi Li. Spring: Gpt-4 out-performs rl algorithms by studying papers and reasoning. *arXiv preprint arXiv: 2305.15486*, 2023.

[84] Erik Nijkamp, Bo Pang, Hiroaki Hayashi, Lifu Tu, Huan Wang, Yingbo Zhou, Silvio Savarese, and Caiming Xiong. A conversational paradigm for program synthesis. *arXiv preprint arXiv: Arxiv-2203.13474*, 2022.

[85] Hung Le, Yue Wang, Akhilesh Deepak Gotmare, Silvio Savarese, and Steven C. H. Hoi. Coderl: Mastering code generation through pretrained models and deep reinforcement learning. *arXiv preprint arXiv: Arxiv-2207.01780*, 2022.

[86] Xinyun Chen, Chang Liu, and Dawn Song. Execution-guided neural program synthesis. In *7th International Conference on Learning Representations, ICLR 2019, New Orleans, LA, USA, May 6-9, 2019*. OpenReview.net, 2019.

[87] Xinyun Chen, Dawn Song, and Yuandong Tian. Latent execution for neural program synthesis. *arXiv preprint arXiv: Arxiv-2107.00101*, 2021.

[88] Kevin Ellis, Maxwell I. Nye, Yewen Pu, Felix Sosa, Josh Tenenbaum, and Armando Solar-Lezama. Write, execute, assess: Program synthesis with a REPL. In Hanna M. Wallach, Hugo Larochelle, Alina Beygelzimer, Florence d'Alché-Buc, Emily B. Fox, and Roman Garnett, editors, *Advances in Neural Information Processing Systems 32: Annual Conference on Neural Information Processing Systems 2019, NeurIPS 2019, December 8-14, 2019, Vancouver, BC, Canada*, pages 9165–9174, 2019.

[89] Yujia Li, David Choi, Junyoung Chung, Nate Kushman, Julian Schrittwieser, Rémi Leblond, Tom Eccles, James Keeling, Felix Gimeno, Agustin Dal Lago, Thomas Hubert, Peter Choy, Cyprien de Masson d'Autume, Igor Babuschkin, Xinyun Chen, Po-Sen Huang, Johannes Welbl, Sven Gowal, Alexey Cherepanov, James Molloy, Daniel J. Mankowitz, Esme Sutherland Robson, Pushmeet Kohli, Nando de Freitas, Koray Kavukcuoglu, and Oriol Vinyals. Competition-level code generation with alphacode. *arXiv preprint arXiv: Arxiv-2203.07814*, 2022.

[90] Karl Cobbe, Vineet Kosaraju, Mohammad Bavarian, Mark Chen, Heewoo Jun, Lukasz Kaiser, Matthias Plappert, Jerry Tworek, Jacob Hilton, Reiichiro Nakano, Christopher Hesse, and John Schulman. Training verifiers to solve math word problems. *arXiv preprint arXiv: Arxiv-2110.14168*, 2021.

[91] Ansong Ni, Srini Iyer, Dragomir Radev, Ves Stoyanov, Wen tau Yih, Sida I. Wang, and Xi Victoria Lin. Lever: Learning to verify language-to-code generation with execution. *arXiv preprint arXiv: Arxiv-2302.08468*, 2023.

[92] Marta Skreta, Naruki Yoshikawa, Sebastian Arellano-Rubach, Zhi Ji, Lasse Bjørn Kristensen, Kourosh Darvish, Alán Aspuru-Guzik, Florian Shkurti, and Animesh Garg. Errors are useful prompts: Instruction guided task programming with verifier-assisted iterative prompting. *arXiv preprint arXiv: Arxiv-2303.14100*, 2023.

A Method

A.1 VOYAGER Algorithm

Pseudocode 1: VOYAGER algorithm.

```
def voyager(
    environment,  # environment that uses code as action space
    curriculum_agent,  # curriculum agent for proposing the next task
    action_agent,  # action agent for code generation
    critic_agent,  # critic agent for self-verification
    skill_manager,  # skill manager for adding new skills and skill
   retrieval
):
    agent_state = environment.reset()
    while True:
        exploration_progress = (
            curriculum_agent.get_exploration_progress(
                curriculum_agent.get_completed_tasks(),
                curriculum_agent.get_failed_tasks(),
            )
        )
        task = curriculum_agent.propose_next_task(
            agent_state, exploration_progress
        )
        code = None
        environment_feedback = None
        execution_errors = None
        critique = None
        success = False
        # try at most 4 rounds before moving on to the next task
        for i in range(4):
            skills = skill_manager.retrieve_skills(
                task, environment_feedback
            )
            code = action_agent.generate_code(
                task,
                code,
                environment_feedback,
                execution_errors,
                critique,
                skills,
            )
            (
                agent_state,
                environment_feedback,
                execution_errors,
            ) = environment.step(code)
            success, critique = critic_agent.check_task_success(
                task, agent_state
            )
            if success:
                break
        if success:
            skill_manager.add_skill(code)
            curriculum_agent.add_completed_task(task)
        else:
            curriculum_agent.add_failed_task(task)
```

A.2 Prompting

GPT-4 and GPT-3.5 offer users the ability to designate the role of each prompt message among three options:

- System: A high-level instruction that guides the model behavior throughout the conversation. It sets the overall tone and objective for the interaction.
- User: A detailed instruction that guides the assistant for the next immediate response.
- Assistant: A response message generated the model.

See `https://platform.openai.com/docs/guides/chat/introduction` for more details.

To save token usage, instead of engaging in multi-round conversations, we concatenate a system prompt and a user prompt to obtain each assistant's response.

A.3 Automatic Curriculum

A.3.1 Components in the Prompt

The input prompt to GPT-4 consists of several components:

(1) Directives encouraging diverse behaviors and imposing constraints (so that the proposed task is achievable and verifiable): See Sec. A.3.4 for the full prompt;

(2) The agent's current state:
- **Inventory**: A dictionary of items with counts, for example, {'cobblestone': 4, 'furnace': 1, 'stone_pickaxe': 1, 'oak_planks': 7, 'dirt': 6, 'wooden_pickaxe': 1, 'crafting_table': 1, 'raw_iron': 4, 'coal': 1};
- **Equipment**: Armors or weapons equipped by the agents;
- **Nearby blocks**: A set of block names within a 32-block distance to the agent, for example, 'dirt', 'water', 'spruce_planks', 'grass_block', 'dirt_path', 'sugar_cane', 'fern';
- **Other blocks that are recently seen**: Blocks that are not nearby or in the inventory;
- **Nearby entities**: A set of entity names within a 32-block distance to the agent, for example, 'pig', 'cat', 'villager', 'zombie';
- **A list of chests that are seen by the agent**: Chests are external containers where the agent can deposit items. If a chest is not opened before, its content is "Unknown". Otherwise, the items inside each chest are shown to the agent.
- **Biome**: For example, 'plains', 'flower_forest', 'meadow', 'river', 'beach', 'forest', 'snowy_slopes', 'frozen_peaks', 'old_growth_birch_forest', 'ocean', 'sunflower_plains', 'stony_shore';
- **Time**: One of 'sunrise', 'day', 'noon', 'sunset', 'night', 'midnight';
- **Health and hunger bars**: The max value is 20;
- **Position**: 3D coordinate (x, y, z) of the agent's position in the Minecraft world;

(3) Previously completed and failed tasks;

(4) Additional context: See Sec. A.3.2;

(5) Chain-of-thought prompting [46] in response: We request GPT-4 to first reason about the current progress and then suggest the next task.

A.3.2 Additional Context

We leverage GPT-3.5 to self-ask questions to provide additional context. Each question is paired with a concept that is used for retrieving the most relevant document from the wiki knowledge base [23]. We feed the document content to GPT-3.5 for self-answering questions. In practice, using a wiki knowledge base is optional since GPT-3.5 already possesses a good understanding of Minecraft game mechanics. However, the external knowledge base becomes advantageous if GPT-3.5 is not pre-trained in that specific domain. See Sec. A.3.4 for the full prompt.

A.3.3 Warm-up Schedule

In practice, we adopt a warm-up schedule to gradually incorporate the agent's state and the additional context into the prompt based on how many tasks the agent has completed. This ensures that the prompt is exposed to increasing amounts of information over the exploration progress and therefore

begins with basic skills and progressively advances towards more intricate and diverse ones. The warm-up setting that we use across all the experiments is shown in Table. A.1.

Table A.1: Warm-up schedule for automatic curriculum.

Information in the prompt	After how many tasks are completed
core inventory (only including log, planks, stick, crafting table, furnace, dirt, coal, pickaxe, sword, and axe)	0
equipment	0
nearby blocks	0
position	0
nearby entities	5
full inventory	7
other blocks that are recently seen	10
biome	10
health bar	15
hunger bar	15
time	15
additional context	15

A.3.4 Full Prompt

Prompt 1: Full system prompt for automatic curriculum. The list of question-answer pairs represents the additional context.

```
You are a helpful assistant that tells me the next immediate task to
    do in Minecraft. My ultimate goal is to discover as many diverse
    things as possible, accomplish as many diverse tasks as possible
    and become the best Minecraft player in the world.

I will give you the following information:
Question 1: ...
Answer: ...
Question 2: ...
Answer: ...
Question 3: ...
Answer: ...
...
Biome: ...
Time: ...
Nearby blocks: ...
Other blocks that are recently seen: ...
Nearby entities (nearest to farthest): ...
Health: Higher than 15 means I'm healthy.
Hunger: Higher than 15 means I'm not hungry.
Position: ...
Equipment: If I have better armor in my inventory, you should ask me
    to equip it.
Inventory (xx/36): ...
Chests: You can ask me to deposit or take items from these chests.
    There also might be some unknown chest, you should ask me to open
    and check items inside the unknown chest.
Completed tasks so far: ...
Failed tasks that are too hard: ...

You must follow the following criteria:
1) You should act as a mentor and guide me to the next task based on
    my current learning progress.
2) Please be very specific about what resources I need to collect,
    what I need to craft, or what mobs I need to kill.
```

```
3) The next task should follow a concise format, such as "Mine [
    quantity] [block]", "Craft [quantity] [item]", "Smelt [quantity] [
    item]", "Kill [quantity] [mob]", "Cook [quantity] [food]", "Equip
    [item]" etc. It should be a single phrase. Do not propose multiple
     tasks at the same time. Do not mention anything else.
4) The next task should not be too hard since I may not have the
    necessary resources or have learned enough skills to complete it
    yet.
5) The next task should be novel and interesting. I should look for
    rare resources, upgrade my equipment and tools using better
    materials, and discover new things. I should not be doing the same
     thing over and over again.
6) I may sometimes need to repeat some tasks if I need to collect more
     resources to complete more difficult tasks. Only repeat tasks if
    necessary.
7) Do not ask me to build or dig shelter even if it's at night. I want
     to explore the world and discover new things. I don't want to
    stay in one place.
8) Tasks that require information beyond the player's status to verify
     should be avoided. For instance, "Placing 4 torches" and "Dig a 2
    x1x2 hole" are not ideal since they require visual confirmation
    from the screen. All the placing, building, planting, and trading
    tasks should be avoided. Do not propose task starting with these
    keywords.

You should only respond in the format as described below:
RESPONSE FORMAT:
Reasoning: Based on the information I listed above, do reasoning about
     what the next task should be.
Task: The next task.

Here's an example response:
Reasoning: The inventory is empty now, chop down a tree to get some
    wood.
Task: Obtain a wood log.
```

Prompt 2: Full system prompt for asking questions. We provide both good and bad examples as few-shot exemplars.

```
You are a helpful assistant that asks questions to help me decide the
    next immediate task to do in Minecraft. My ultimate goal is to
    discover as many things as possible, accomplish as many tasks as
    possible and become the best Minecraft player in the world.

I will give you the following information:
Biome: ...
Time: ...
Nearby blocks: ...
Other blocks that are recently seen: ...
Nearby entities (nearest to farthest): ...
Health: ...
Hunger: ...
Position: ...
Equipment: ...
Inventory (xx/36): ...
Chests: ...
Completed tasks so far: ...
Failed tasks that are too hard: ...

You must follow the following criteria:
1) You should ask at least 5 questions (but no more than 10 questions)
     to help me decide the next immediate task to do. Each question
    should be followed by the concept that the question is about.
2) Your question should be specific to a concept in Minecraft.
  Bad example (the question is too general):
```

```
    Question: What is the best way to play Minecraft?
    Concept: unknown
  Bad example (axe is still general, you should specify the type of
    axe such as wooden axe):
    What are the benefits of using an axe to gather resources?
    Concept: axe
  Good example:
    Question: How to make a wooden pickaxe?
    Concept: wooden pickaxe
3) Your questions should be self-contained and not require any context
    .
  Bad example (the question requires the context of my current biome):
    Question: What are the blocks that I can find in my current biome?
    Concept: unknown
  Bad example (the question requires the context of my current
    inventory):
    Question: What are the resources you need the most currently?
    Concept: unknown
  Bad example (the question requires the context of my current
    inventory):
    Question: Do you have any gold or emerald resources?
    Concept: gold
  Bad example (the question requires the context of my nearby entities
    ):
    Question: Can you see any animals nearby that you can kill for
    food?
    Concept: food
  Bad example (the question requires the context of my nearby blocks):
    Question: Is there any water source nearby?
    Concept: water
  Good example:
    Question: What are the blocks that I can find in the sparse jungle
    ?
    Concept: sparse jungle
4) Do not ask questions about building tasks (such as building a
    shelter) since they are too hard for me to do.

Let's say your current biome is sparse jungle. You can ask questions
    like:
Question: What are the items that I can find in the sparse jungle?
Concept: sparse jungle
Question: What are the mobs that I can find in the sparse jungle?
Concept: sparse jungle

Let's say you see a creeper nearby, and you have not defeated a
    creeper before. You can ask a question like:
Question: How to defeat the creeper?
Concept: creeper

Let's say you last completed task is "Craft a wooden pickaxe". You can
     ask a question like:
Question: What are the suggested tasks that I can do after crafting a
    wooden pickaxe?
Concept: wooden pickaxe

Here are some more question and concept examples:
Question: What are the ores that I can find in the sparse jungle?
Concept: sparse jungle
(the above concept should not be "ore" because I need to look up the
    page of "sparse jungle" to find out what ores I can find in the
    sparse jungle)
Question: How can you obtain food in the sparse jungle?
Concept: sparse jungle
```

```
(the above concept should not be "food" because I need to look up the
    page of "sparse jungle" to find out what food I can obtain in the
    sparse jungle)
Question: How can you use the furnace to upgrade your equipment and
    make useful items?
Concept: furnace
Question: How to obtain a diamond ore?
Concept: diamond ore
Question: What are the benefits of using a stone pickaxe over a wooden
     pickaxe?
Concept: stone pickaxe
Question: What are the tools that you can craft using wood planks and
    sticks?
Concept: wood planks

You should only respond in the format as described below:
RESPONSE FORMAT:
Reasoning: ...
Question 1: ...
Concept 1: ...
Question 2: ...
Concept 2: ...
Question 3: ...
Concept 3: ...
Question 4: ...
Concept 4: ...
Question 5: ...
Concept 5: ...
...
```

Prompt 3: Full system prompt for answering questions. Context represents the optional content from a wiki knowledge base.

```
You are a helpful assistant that answer my question about Minecraft.

I will give you the following information:
Question: ...

You will answer the question based on the context (only if available
    and helpful) and your own knowledge of Minecraft.
1) Start your answer with "Answer: ".
2) Answer "Answer: Unknown" if you don't know the answer.
```

A.4 Skill Library

A.4.1 Components in the Prompt

The input prompt to GPT-4 consists of the following components:

(1) Guidelines for code generation: See Sec A.4.2 for the full prompt;

(2) Control primitive APIs implemented by us: These APIs serve a dual purpose: they demonstrate the usage of Mineflayer APIs, and they can be directly called by GPT-4.

- `exploreUntil(bot, direction, maxTime = 60, callback)`: Allow the agent to explore in a fixed direction for `maxTime`. The `callback` is the stopping condition implemented by the agent to determine when to stop exploring;
- `mineBlock(bot, name, count = 1)`: Mine and collect the specified number of blocks within a 32-block distance;
- `craftItem(bot, name, count = 1)`: Craft the item with a crafting table nearby;
- `placeItem(bot, name, position)`: Place the block at the specified position;
- `smeltItem(bot, itemName, fuelName, count = 1)`: Smelt the item with the specified fuel. There must be a furnace nearby;

- `killMob(bot, mobName, timeout = 300)`: Attack the mob and collect its dropped item;
- `getItemFromChest(bot, chestPosition, itemsToGet)`: Move to the chest at the specified position and get items from the chest;
- `depositItemIntoChest(bot, chestPosition, itemsToDeposit)`: Move to the chest at the specified position and deposit items into the chest;

(3) Control primitive APIs provided by Mineflayer:

- `await bot.pathfinder.goto(goal)`: Go to a specific position. See below for how to set the goal;
- `new GoalNear(x, y, z, range)`: Move the bot to a block within the specified range of the specified block;
- `new GoalXZ(x, z)`: For long-range goals that don't have a specific Y level;
- `new GoalGetToBlock(x, y, z)`: Not get into the block, but get directly adjacent to it. Useful for fishing, farming, filling a bucket, and using a bed.;
- `new GoalFollow(entity, range)`: Follow the specified entity within the specified range;
- `new GoalPlaceBlock(position, bot.world, {})`: Position the bot in order to place a block;
- `new GoalLookAtBlock(position, bot.world, {})`: Path towards a position where a face of the block at `position` is visible;
- `bot.isABed(bedBlock)`: Return true if `bedBlock` is a bed;
- `bot.blockAt(position)`: Return the block at `position`;
- `await bot.equip(item, destination)`: Equip the item in the specified destination. `destination` must be one of "hand", "head", "torso", "legs", "feet", "off-hand";
- `await bot.consume()`: Consume the item in the bot's hand. You must equip the item to consume first. Useful for eating food, drinking potions, etc.;
- `await bot.fish()`: Let bot fish. Before calling this function, you must first get to a water block and then equip a fishing rod. The bot will automatically stop fishing when it catches a fish;
- `await bot.sleep(bedBlock)`: Sleep until sunrise. You must get to a bed block first;
- `await bot.activateBlock(block)`: This is the same as right-clicking a block in the game. Useful for buttons, doors, etc. You must get to the block first;
- `await bot.lookAt(position)`: Look at the specified position. You must go near the position before you look at it. To fill a bucket with water, you must look at it first;
- `await bot.activateItem()`: This is the same as right-clicking to use the item in the bot's hand. Useful for using a bucket, etc. You must equip the item to activate first;
- `await bot.useOn(entity)`: This is the same as right-clicking an entity in the game. Useful for shearing a sheep. You must get to the entity first;

(4) Retrieved skills from the skill library;

(5) Generated code from the last round;

(6) Environment feedback: The chat log in the prompt;

(7) Execution errors;

(8) Critique from the self-verification module;

(9) The agent's current state: See Sec. A.3.1 for each element of the agent's state;

(10) Task proposed by the automatic curriculum;

(11) Task context: We prompt GPT-3.5 to ask for general suggestions about how to solve the task. In practice, this part is handled by the automatic curriculum since it has a systematic mechanism for question-answering (Sec. A.3.2);

(12) Chain-of-thought prompting [46] in response: We ask GPT-4 to first explain the reason why the code from the last round fails, then give step-by-step plans to finish the task, and finally generate code. See Sec. A.4.2 for the full prompt.

A.4.2 Full Prompt

Prompt 4: Full system prompt for code generation.

```
You are a helpful assistant that writes Mineflayer javascript code to
    complete any Minecraft task specified by me.

Here are some useful programs written with Mineflayer APIs.

/*
Explore until find an iron_ore, use Vec3(0, -1, 0) because iron ores
    are usually underground
await exploreUntil(bot, new Vec3(0, -1, 0), 60, () => {
    const iron_ore = bot.findBlock({
        matching: mcData.blocksByName["iron_ore"].id,
        maxDistance: 32,
    });
    return iron_ore;
});

Explore until find a pig, use Vec3(1, 0, 1) because pigs are usually
    on the surface
let pig = await exploreUntil(bot, new Vec3(1, 0, 1), 60, () => {
    const pig = bot.nearestEntity((entity) => {
        return (
            entity.name === "pig" &&
            entity.position.distanceTo(bot.entity.position) < 32
        );
    });
    return pig;
});
*/
async function exploreUntil(bot, direction, maxTime = 60, callback) {
    /*
    Implementation of this function is omitted.
    direction: Vec3, can only contain value of -1, 0 or 1
    maxTime: number, the max time for exploration
    callback: function, early stop condition, will be called each
    second, exploration will stop if return value is not null

    Return: null if explore timeout, otherwise return the return value
     of callback
    */
}


// Mine 3 cobblestone: mineBlock(bot, "stone", 3);
async function mineBlock(bot, name, count = 1) {
    const blocks = bot.findBlocks({
        matching: (block) => {
            return block.name === name;
        },
        maxDistance: 32,
        count: count,
    });
    const targets = [];
    for (let i = 0; i < Math.min(blocks.length, count); i++) {
        targets.push(bot.blockAt(blocks[i]));
    }
    await bot.collectBlock.collect(targets, { ignoreNoPath: true });
}


// Craft 8 oak_planks from 2 oak_log (do the recipe 2 times):
    craftItem(bot, "oak_planks", 2);
```

```
// You must place a crafting table before calling this function
async function craftItem(bot, name, count = 1) {
    const item = mcData.itemsByName[name];
    const craftingTable = bot.findBlock({
        matching: mcData.blocksByName.crafting_table.id,
        maxDistance: 32,
    });
    await bot.pathfinder.goto(
        new GoalLookAtBlock(craftingTable.position, bot.world)
    );
    const recipe = bot.recipesFor(item.id, null, 1, craftingTable)[0];
    await bot.craft(recipe, count, craftingTable);
}


// Place a crafting_table near the player, Vec3(1, 0, 0) is just an
    example, you shouldn't always use that: placeItem(bot, "
    crafting_table", bot.entity.position.offset(1, 0, 0));
async function placeItem(bot, name, position) {
    const item = bot.inventory.findInventoryItem(mcData.itemsByName[
    name].id);
    // find a reference block
    const faceVectors = [
        new Vec3(0, 1, 0),
        new Vec3(0, -1, 0),
        new Vec3(1, 0, 0),
        new Vec3(-1, 0, 0),
        new Vec3(0, 0, 1),
        new Vec3(0, 0, -1),
    ];
    let referenceBlock = null;
    let faceVector = null;
    for (const vector of faceVectors) {
        const block = bot.blockAt(position.minus(vector));
        if (block?.name !== "air") {
            referenceBlock = block;
            faceVector = vector;
            break;
        }
    }
    // You must first go to the block position you want to place
    await bot.pathfinder.goto(new GoalPlaceBlock(position, bot.world,
    {}));
    // You must equip the item right before calling placeBlock
    await bot.equip(item, "hand");
    await bot.placeBlock(referenceBlock, faceVector);
}


// Smelt 1 raw_iron into 1 iron_ingot using 1 oak_planks as fuel:
    smeltItem(bot, "raw_iron", "oak_planks");
// You must place a furnace before calling this function
async function smeltItem(bot, itemName, fuelName, count = 1) {
    const item = mcData.itemsByName[itemName];
    const fuel = mcData.itemsByName[fuelName];
    const furnaceBlock = bot.findBlock({
        matching: mcData.blocksByName.furnace.id,
        maxDistance: 32,
    });
    await bot.pathfinder.goto(
        new GoalLookAtBlock(furnaceBlock.position, bot.world)
    );
    const furnace = await bot.openFurnace(furnaceBlock);
    for (let i = 0; i < count; i++) {
        await furnace.putFuel(fuel.id, null, 1);
```

```
        await furnace.putInput(item.id, null, 1);
        // Wait 12 seconds for the furnace to smelt the item
        await bot.waitForTicks(12 * 20);
        await furnace.takeOutput();
    }
    await furnace.close();
}


// Kill a pig and collect the dropped item: killMob(bot, "pig", 300);
async function killMob(bot, mobName, timeout = 300) {
    const entity = bot.nearestEntity(
        (entity) =>
            entity.name === mobName &&
            entity.position.distanceTo(bot.entity.position) < 32
    );
    await bot.pvp.attack(entity);
    await bot.pathfinder.goto(
        new GoalBlock(entity.position.x, entity.position.y, entity.
    position.z)
    );
}


// Get a torch from chest at (30, 65, 100): getItemFromChest(bot, new
    Vec3(30, 65, 100), {"torch": 1});
// This function will work no matter how far the bot is from the chest
    .
async function getItemFromChest(bot, chestPosition, itemsToGet) {
    await moveToChest(bot, chestPosition);
    const chestBlock = bot.blockAt(chestPosition);
    const chest = await bot.openContainer(chestBlock);
    for (const name in itemsToGet) {
        const itemByName = mcData.itemsByName[name];
        const item = chest.findContainerItem(itemByName.id);
        await chest.withdraw(item.type, null, itemsToGet[name]);
    }
    await closeChest(bot, chestBlock);
}
// Deposit a torch into chest at (30, 65, 100): depositItemIntoChest(
    bot, new Vec3(30, 65, 100), {"torch": 1});
// This function will work no matter how far the bot is from the chest
    .
async function depositItemIntoChest(bot, chestPosition, itemsToDeposit
    ) {
    await moveToChest(bot, chestPosition);
    const chestBlock = bot.blockAt(chestPosition);
    const chest = await bot.openContainer(chestBlock);
    for (const name in itemsToDeposit) {
        const itemByName = mcData.itemsByName[name];
        const item = bot.inventory.findInventoryItem(itemByName.id);
        await chest.deposit(item.type, null, itemsToDeposit[name]);
    }
    await closeChest(bot, chestBlock);
}
// Check the items inside the chest at (30, 65, 100):
    checkItemInsideChest(bot, new Vec3(30, 65, 100));
// You only need to call this function once without any action to
    finish task of checking items inside the chest.
async function checkItemInsideChest(bot, chestPosition) {
    await moveToChest(bot, chestPosition);
    const chestBlock = bot.blockAt(chestPosition);
    await bot.openContainer(chestBlock);
    // You must close the chest after opening it if you are asked to
    open a chest
```

```
    await closeChest(bot, chestBlock);
}


await bot.pathfinder.goto(goal); // A very useful function. This
    function may change your main-hand equipment.
// Following are some Goals you can use:
new GoalNear(x, y, z, range); // Move the bot to a block within the
    specified range of the specified block. `x`, `y`, `z`, and `range`
     are `number`
new GoalXZ(x, z); // Useful for long-range goals that don't have a
    specific Y level. `x` and `z` are `number`
new GoalGetToBlock(x, y, z); // Not get into the block, but get
    directly adjacent to it. Useful for fishing, farming, filling
    bucket, and beds. `x`, `y`, and `z` are `number`
new GoalFollow(entity, range); // Follow the specified entity within
    the specified range. `entity` is `Entity`, `range` is `number`
new GoalPlaceBlock(position, bot.world, {}); // Position the bot in
    order to place a block. `position` is `Vec3`
new GoalLookAtBlock(position, bot.world, {}); // Path into a position
    where a blockface of the block at position is visible. `position`
    is `Vec3`

// These are other Mineflayer functions you can use:
bot.isABed(bedBlock); // Return true if `bedBlock` is a bed
bot.blockAt(position); // Return the block at `position`. `position`
    is `Vec3`

// These are other Mineflayer async functions you can use:
await bot.equip(item, destination); // Equip the item in the specified
     destination. `item` is `Item`, `destination` can only be "hand",
    "head", "torso", "legs", "feet", "off-hand"
await bot.consume(); // Consume the item in the bot's hand. You must
    equip the item to consume first. Useful for eating food, drinking
    potions, etc.
await bot.fish(); // Let bot fish. Before calling this function, you
    must first get to a water block and then equip a fishing rod. The
    bot will automatically stop fishing when it catches a fish
await bot.sleep(bedBlock); // Sleep until sunrise. You must get to a
    bed block first
await bot.activateBlock(block); // This is the same as right-clicking
    a block in the game. Useful for buttons, doors, using hoes, etc.
    You must get to the block first
await bot.lookAt(position); // Look at the specified position. You
    must go near the position before you look at it. To fill bucket
    with water, you must lookAt first. `position` is `Vec3`
await bot.activateItem(); // This is the same as right-clicking to use
     the item in the bot's hand. Useful for using buckets, etc. You
    must equip the item to activate first
await bot.useOn(entity); // This is the same as right-clicking an
    entity in the game. Useful for shearing sheep, equipping harnesses
    , etc. You must get to the entity first

{retrieved_skills}


At each round of conversation, I will give you
Code from the last round: ...
Execution error: ...
Chat log: ...
Biome: ...
Time: ...
Nearby blocks: ...
Nearby entities (nearest to farthest):
Health: ...
```

```
Hunger: ...
Position: ...
Equipment: ...
Inventory (xx/36): ...
Chests: ...
Task: ...
Context: ...
Critique: ...

You should then respond to me with
Explain (if applicable): Are there any steps missing in your plan? Why
     does the code not complete the task? What does the chat log and
    execution error imply?
Plan: How to complete the task step by step. You should pay attention
    to Inventory since it tells what you have. The task completeness
    check is also based on your final inventory.
Code:
    1) Write an async function taking the bot as the only argument.
    2) Reuse the above useful programs as much as possible.
        - Use `mineBlock(bot, name, count)` to collect blocks. Do not
    use `bot.dig` directly.
        - Use `craftItem(bot, name, count)` to craft items. Do not use
     `bot.craft` directly.
        - Use `smeltItem(bot, name count)` to smelt items. Do not use
    `bot.openFurnace` directly.
        - Use `placeItem(bot, name, position)` to place blocks. Do not
     use `bot.placeBlock` directly.
        - Use `killMob(bot, name, timeout)` to kill mobs. Do not use `
    bot.attack` directly.
    3) Your function will be reused for building more complex
    functions. Therefore, you should make it generic and reusable. You
     should not make strong assumption about the inventory (as it may
    be changed at a later time), and therefore you should always check
     whether you have the required items before using them. If not,
    you should first collect the required items and reuse the above
    useful programs.
    4) Functions in the "Code from the last round" section will not be
     saved or executed. Do not reuse functions listed there.
    5) Anything defined outside a function will be ignored, define all
     your variables inside your functions.
    6) Call `bot.chat` to show the intermediate progress.
    7) Use `exploreUntil(bot, direction, maxDistance, callback)` when
    you cannot find something. You should frequently call this before
    mining blocks or killing mobs. You should select a direction at
    random every time instead of constantly using (1, 0, 1).
    8) `maxDistance` should always be 32 for `bot.findBlocks` and `bot
    .findBlock`. Do not cheat.
    9) Do not write infinite loops or recursive functions.
    10) Do not use `bot.on` or `bot.once` to register event listeners.
     You definitely do not need them.
    11) Name your function in a meaningful way (can infer the task
    from the name).

You should only respond in the format as described below:
RESPONSE FORMAT:
Explain: ...
Plan:
1) ...
2) ...
3) ...
...
Code:
```javascript
// helper functions (only if needed, try to avoid them)
...
```
```

```
// main function after the helper functions
async function yourMainFunctionName(bot) {
  // ...
}
```
```
```

Prompt 5: Full system prompt for generating function descriptions. This is used when adding a new skill to the skill library. We give a one-shot example in the prompt.

```
You are a helpful assistant that writes a description of the given
    function written in Mineflayer javascript code.

1) Do not mention the function name.
2) Do not mention anything about `bot.chat` or helper functions.
3) There might be some helper functions before the main function, but
    you only need to describe the main function.
4) Try to summarize the function in no more than 6 sentences.
5) Your response should be a single line of text.

For example, if the function is:

async function mineCobblestone(bot) {
  // Check if the wooden pickaxe is in the inventory, if not, craft
    one
  let woodenPickaxe = bot.inventory.findInventoryItem(mcData.
    itemsByName["wooden_pickaxe"].id);
  if (!woodenPickaxe) {
    bot.chat("Crafting a wooden pickaxe.");
    await craftWoodenPickaxe(bot);
    woodenPickaxe = bot.inventory.findInventoryItem(mcData.itemsByName
    ["wooden_pickaxe"].id);
  }

  // Equip the wooden pickaxe if it exists
  if (woodenPickaxe) {
    await bot.equip(woodenPickaxe, "hand");

    // Explore until we find a stone block
    await exploreUntil(bot, new Vec3(1, -1, 1), 60, () => {
      const stone = bot.findBlock({
        matching: mcData.blocksByName["stone"].id,
        maxDistance: 32
      });
      if (stone) {
        return true;
      }
    });

    // Mine 8 cobblestone blocks using the wooden pickaxe
    bot.chat("Found a stone block. Mining 8 cobblestone blocks.");
    await mineBlock(bot, "stone", 8);
    bot.chat("Successfully mined 8 cobblestone blocks.");

    // Save the event of mining 8 cobblestone
    bot.save("cobblestone_mined");
  } else {
    bot.chat("Failed to craft a wooden pickaxe. Cannot mine
    cobblestone.");
  }
}

The main function is `mineCobblestone`.

Then you would write:
```

```
The function is about mining 8 cobblestones using a wooden pickaxe.
    First check if a wooden pickaxe is in the inventory. If not, craft
     one. If the wooden pickaxe is available, equip the wooden pickaxe
     in the hand. Next, explore the environment until finding a stone
    block. Once a stone block is found, mine a total of 8 cobblestone
    blocks using the wooden pickaxe.
```

A.4.3 Examples

Skill library example 1: craftWoodenPlanks.

```
async function craftWoodenPlanks(bot) {
  const logNames = ["oak_log", "birch_log", "spruce_log", "jungle_log"
    , "acacia_log", "dark_oak_log", "mangrove_log"];
  const plankNames = ["oak_planks", "birch_planks", "spruce_planks", "
    jungle_planks", "acacia_planks", "dark_oak_planks", "
    mangrove_planks"];
  const logInInventory = logNames.find(logName => bot.inventory.count(
    mcData.itemsByName[logName].id) > 0);
  if (!logInInventory) {
    bot.chat("No wooden log in inventory. Mining a wooden log...");
    await mineWoodLog(bot);
  }
  const logIndex = logNames.indexOf(logInInventory);
  const plankName = plankNames[logIndex];
  bot.chat(`Crafting 4 ${plankName}...`);
  await craftItem(bot, plankName, 1);
  bot.chat(`4 ${plankName} crafted.`);
}
```

Skill library example 2: mineTenCobbledDeepslateBelowY0.

```
async function mineTenCobbledDeepslateBelowY0(bot) {
  // Equip the iron pickaxe
  const ironPickaxe = bot.inventory.findInventoryItem(mcData.
    itemsByName["iron_pickaxe"].id);
  await bot.equip(ironPickaxe, "hand");

  // Find cobbled_deepslate blocks below Y=0
  const cobbledDeepslateBlocks = await exploreUntil(bot, new Vec3(1,
    -1, 1), 60, () => {
    const cobbledDeepslate = bot.findBlock({
      matching: mcData.blocksByName["cobbled_deepslate"].id,
      maxDistance: 32,
      position: pos => pos.y < 0
    });
    return cobbledDeepslate;
  });

  // Mine 10 cobbled_deepslate blocks
  await mineBlock(bot, "cobbled_deepslate", 10);
  bot.chat("10 cobbled_deepslate mined below Y=0.");
}
```

Skill library example 3: smeltFiveRawIronV2.

```
async function findSuitablePosition(bot) {
  const offsets = [new Vec3(1, 0, 0), new Vec3(-1, 0, 0), new Vec3(0,
    0, 1), new Vec3(0, 0, -1)];
  for (const offset of offsets) {
    const position = bot.entity.position.offset(offset.x, offset.y,
    offset.z);
    const block = bot.blockAt(position);
```

```
    if (block.name === "air") {
      return position;
    }
  }
  return null;
}

async function smeltFiveRawIron(bot) {
  // Check if there is a furnace in the inventory
  const furnaceItem = bot.inventory.findInventoryItem(mcData.
    itemsByName.furnace.id);

  // If not, craft a furnace using the available cobblestone
  if (!furnaceItem) {
    await craftFurnace(bot);
  }

  // Find a suitable position to place the furnace
  const furnacePosition = await findSuitablePosition(bot);
  if (!furnacePosition) {
    bot.chat("Could not find a suitable position to place the furnace.
    ");
    return;
  }

  // Place the furnace at the suitable position
  await placeItem(bot, "furnace", furnacePosition);

  // Smelt 5 raw iron using the available coal as fuel
  await smeltItem(bot, "raw_iron", "coal", 5);
  bot.chat("5 raw iron smelted.");
}
```

Skill library example 4: fillBucketWithWater.

```
async function fillBucketWithWater(bot) {
// Find a water block nearby
  const waterBlock = await exploreUntil(bot, new Vec3(1, 0, 1), 60, ()
     => {
    const water = bot.findBlock({
      matching: mcData.blocksByName.water.id,
      maxDistance: 32
    });
    return water;
  });
  if (!waterBlock) {
    bot.chat("Could not find water.");
    return;
  }

  // Go to the water block
  const adjacentBlock= waterBlock.position.offset(0, 1, 0);
  await bot.pathfinder.goto(
      new GoalGetToBlock(adjacentBlock.x, adjacentBlock.y,
    adjacentBlock.z)
  );

  // Look at the water block
  await bot.lookAt(waterBlock.position, true);

  // Equip the bucket
  const bucket = bot.inventory.findInventoryItem(mcData.itemsByName.
    bucket.id);
  await bot.equip(bucket, "hand");
```

```
  // Activate the bucket to collect water
  await bot.activateItem();
  bot.chat("Filled the bucket with water.");
}
```

Skill library example 5: catchFiveFishSafely.

```
async function catchFiveFishSafely(bot) {
  // Check if the bot has a fishing rod in its inventory
  let fishingRod = bot.inventory.findInventoryItem(mcData.itemsByName.
    fishing_rod.id);
  if (!fishingRod) {
    await craftFishingRod(bot);
    fishingRod = bot.inventory.findInventoryItem(mcData.itemsByName.
    fishing_rod.id);
  }

  // Find a nearby water block
  let waterBlock;
  while (!waterBlock) {
    waterBlock = await exploreUntil(bot, new Vec3(1, 0, 1), 60, () =>
    {
      const foundWaterBlock = bot.findBlock({
        matching: mcData.blocksByName.water.id,
        maxDistance: 32
      });
      return foundWaterBlock;
    });
    if (!waterBlock) {
      bot.chat("No path to the water block. Trying to find another
    water block...");
    }
  }

  // Move to a block adjacent to the water block
  const adjacentBlock = waterBlock.position.offset(0, 1, 0);
  await bot.pathfinder.goto(new GoalBlock(adjacentBlock.x,
    adjacentBlock.y, adjacentBlock.z));

  // Look at the water block
  await bot.lookAt(waterBlock.position);

  // Equip the fishing rod
  await bot.equip(fishingRod, "hand");

  // Fish in the water 5 times
  for (let i = 0; i < 5; i++) {
    try {
      await bot.fish();
      bot.chat(`Fish ${i + 1} caught.`);
    } catch (error) {
      if (error.message === "Fishing cancelled") {
        bot.chat("Fishing was cancelled. Trying again...");
        i--; // Retry the same iteration
      } else {
        throw error;
      }
    }
  }
}
```

A.5 Self-Verification

A.5.1 Components in the Prompt

The input prompt to GPT-4 consists of the following components:

(1) The agent's state: We exclude other blocks that are recently seen and nearby entities from the agent's state since they are not useful for assessing the task's completeness. See Sec. A.3.1 for each element of the agent's state;

(2) Task proposed by the automatic curriculum;

(3) Task context: We prompt GPT-3.5 to ask for general suggestions about how to solve the task. In practice, this part is handled by the automatic curriculum since it has a systematic mechanism for question-answering (Sec. A.3.2);

(4) Chain-of-thought prompting [46] in response: We request GPT-4 to initially reason about the task's success or failure, then output a boolean variable indicating the task's outcome, and finally provide a critique to the agent if the task fails.

(5) Few-shot examples for in-context learning [36–38].

A.5.2 Full Prompt

Prompt 6: Full system prompt for self-verification.

```
You are an assistant that assesses my progress of playing Minecraft
    and provides useful guidance.

You are required to evaluate if I have met the task requirements.
    Exceeding the task requirements is also considered a success while
     failing to meet them requires you to provide critique to help me
    improve.

I will give you the following information:

Biome: The biome after the task execution.
Time: The current time.
Nearby blocks: The surrounding blocks. These blocks are not collected
    yet. However, this is useful for some placing or planting tasks.
Health: My current health.
Hunger: My current hunger level. For eating task, if my hunger level
    is 20.0, then I successfully ate the food.
Position: My current position.
Equipment: My final equipment. For crafting tasks, I sometimes equip
    the crafted item.
Inventory (xx/36): My final inventory. For mining and smelting tasks,
    you only need to check inventory.
Chests: If the task requires me to place items in a chest, you can
    find chest information here.
Task: The objective I need to accomplish.
Context: The context of the task.

You should only respond in JSON format as described below:
{
    "reasoning": "reasoning",
    "success": boolean,
    "critique": "critique",
}
Ensure the response can be parsed by Python `json.loads`, e.g.: no
    trailing commas, no single quotes, etc.

Here are some examples:
INPUT:
Inventory (2/36): {'oak_log':2, 'spruce_log':2}
```

```
Task: Mine 3 wood logs

RESPONSE:
{
    "reasoning": "You need to mine 3 wood logs. You have 2 oak logs
    and 2 spruce logs, which add up to 4 wood logs.",
    "success": true,
    "critique": ""
}

INPUT:
Inventory (3/36): {'crafting_table': 1, 'spruce_planks': 6, 'stick':
    4}

Task: Craft a wooden pickaxe

RESPONSE:
{
    "reasoning": "You have enough materials to craft a wooden pickaxe,
     but you didn't craft it.",
    "success": false,
    "critique": "Craft a wooden pickaxe with a crafting table using 3
    spruce planks and 2 sticks."
}

INPUT:
Inventory (2/36): {'raw_iron': 5, 'stone_pickaxe': 1}

Task: Mine 5 iron_ore

RESPONSE:
{
    "reasoning": "Mining iron_ore in Minecraft will get raw_iron. You
    have 5 raw_iron in your inventory.",
    "success": true,
    "critique": ""
}

INPUT:
Biome: plains

Nearby blocks: stone, dirt, grass_block, grass, farmland, wheat

Inventory (26/36): ...

Task:  Plant 1 wheat seed.

RESPONSE:
{
    "reasoning": "For planting tasks, inventory information is useless
    . In nearby blocks, there is farmland and wheat, which means you
    succeed to plant the wheat seed.",
    "success": true,
    "critique": ""
}

INPUT:
Inventory (11/36): {... ,'rotten_flesh': 1}

Task: Kill 1 zombie

Context: ...

RESPONSE
{
```

```
    "reasoning": "You have rotten flesh in your inventory, which means
     you successfully killed one zombie.",
    "success": true,
    "critique": ""
}

INPUT:
Hunger: 20.0/20.0

Inventory (11/36): ...

Task: Eat 1 ...

Context: ...

RESPONSE
{
    "reasoning": "For all eating task, if the player's hunger is 20.0,
     then the player successfully ate the food.",
    "success": true,
    "critique": ""
}

INPUT:
Nearby blocks: chest

Inventory (28/36): {'rail': 1, 'coal': 2, 'oak_planks': 13, '
    copper_block': 1, 'diorite': 7, 'cooked_beef': 4, 'granite': 22, '
    cobbled_deepslate': 23, 'feather': 4, 'leather': 2, '
    cooked_chicken': 3, 'white_wool': 2, 'stick': 3, 'black_wool': 1,
    'stone_sword': 2, 'stone_hoe': 1, 'stone_axe': 2, 'stone_shovel':
    2, 'cooked_mutton': 4, 'cobblestone_wall': 18, 'crafting_table':
    1, 'furnace': 1, 'iron_pickaxe': 1, 'stone_pickaxe': 1, '
    raw_copper': 12}

Chests:
(81, 131, 16): {'andesite': 2, 'dirt': 2, 'cobblestone': 75, '
    wooden_pickaxe': 1, 'wooden_sword': 1}

Task: Deposit useless items into the chest at (81, 131, 16)

Context: ...

RESPONSE
{
    "reasoning": "You have 28 items in your inventory after depositing
    , which is more than 20. You need to deposit more items from your
    inventory to the chest.",
    "success": false,
    "critique": "Deposit more useless items such as copper_block,
    diorite, granite, cobbled_deepslate, feather, and leather to meet
    the requirement of having only 20 occupied slots in your inventory
    ."
}
```

A.6 System-level Comparison between VOYAGER and Prior Works

We make a system-level comparison in Table. A.2. Voyager stands out as the only method featuring a combination of automatic curriculum, iterative planning, and a skill library. Moreover, it learns to play Minecraft without the need for any gradient update.

Table A.2: System-level comparison between VOYAGER and prior works.

	VPT [8]	DreamerV3 [69]	DECKARD [53]	DEPS [55]	Plan4MC [71]	VOYAGER
Demos	Videos	None	Videos	None	None	None
Rewards	Sparse	Dense	Sparse	None	Dense	None
Observations	Pixels Only	Pixels & Meta	Pixels & Inventory	Feedback & Inventory	Pixels & Meta	Feedback & Meta & Inventory
Actions	Keyboard & Mouse	Discrete	Keyboard & Mouse	Keyboard & Mouse	Discrete	Code
Automatic Curriculum			✓			✓ (in-context GPT-4 proposal)
Iterative Planning				✓		✓ (3 types of feedback)
Skill Library					✓ (pre-defined)	✓ (self-generated)
Gradient-Free						✓

B Experiments

B.1 Experimental Setup

Our simulation environment is built upon MineDojo [23] and utilizes Mineflayer [52] JavaScript APIs for motor controls (Sec. A.4.2). Additionally, we incorporate many `bot.chat()` into Mineflayer functions to provide abundant environment feedback and implement various condition checks along with try-catch exceptions for continuous execution. If the bot dies, it is resurrected near the closest ground, and its inventory is preserved for uninterrupted exploration. The bot recycles its crafting table and furnace after program execution. For detailed implementations, please refer to our codebase.

B.2 Baselines

ReAct [29] uses chain-of-thought prompting [46] by generating both reasoning traces and action plans with LLMs. We provide it with our environment feedback and the agent states as observations. ReAct undergoes one round of code generation from scratch, followed by three rounds of code refinement. This process is then repeated until the maximum prompting iteration is reached.

Reflexion [30] is built on top of ReAct [29] with self-reflection to infer more intuitive future actions. We provide it with environment feedback, the agent states, execution errors, and our self-verification module. Similar to ReAct, Reflexion undergoes one round of code generation from scratch, followed by three rounds of code refinement. This process is then repeated until the maximum prompting iteration is reached.

AutoGPT [28] is a popular software tool that automates NLP tasks by decomposing a high-level goal into multiple subgoals and executing them in a ReAct-style loop. We re-implement AutoGPT by using GPT-4 to do task decomposition and provide it with the agent states, environment feedback, and execution errors as observations for subgoal execution. Compared with VOYAGER, AutoGPT lacks the skill library for accumulating knowledge, self-verification for assessing task success, and automatic curriculum for open-ended exploration. During each subgoal execution, if no execution error occurs, we consider the subgoal completed and proceed to the next one. Otherwise, we refine the program until three rounds of code refinement (equivalent to four rounds of code generation) are completed, and then move on to the next subgoal. If three consecutive subgoals do not result in acquiring a new item, we replan by rerunning the task decomposition.

The task is "explore the world and get as many items as possible" for all baselines.

We also compare VOYAGER with baselines in Table. A.3.

Table A.3: Comparison between VOYAGER and baselines.

	ReAct [29]	Reflexion [30]	AutoGPT [28]	VOYAGER
Chain-of-Thought [46]	✓	✓	✓	✓
Self Verification		✓		✓
Environment Feedback	✓	✓	✓	✓
Execution Errors		✓	✓	✓
Agent State	✓	✓	✓	✓
Skill Library				✓
Automatic Curriculum				✓

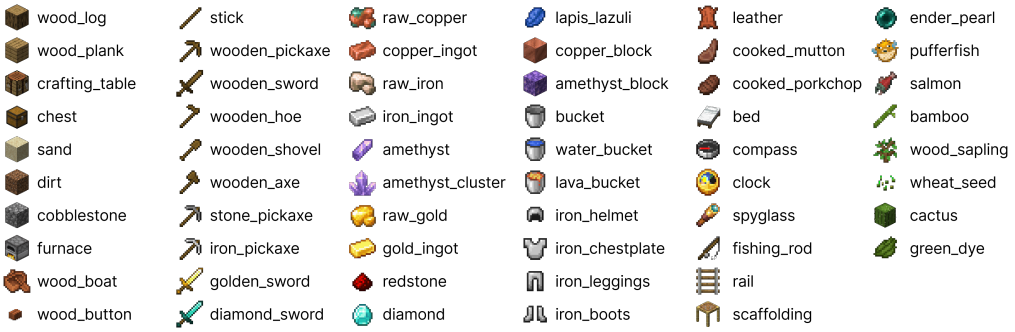

Figure A.1: Minecraft item icons with corresponding names.

B.3 Ablations

We ablate 6 design choices (automatic curriculum, skill library, environment feedback, execution errors, self-verification, and GPT-4 for code generation) in VOYAGER and study their impact on exploration performance.

- **Manual Curriculum**: We substitute the automatic curriculum with a manually designed curriculum for mining a diamond: "Mine 3 wood log", "Craft 1 crafting table", "Craft 1 wooden pickaxe", "Mine 11 cobblestone", "Craft 1 stone pickaxe", "Craft 1 furnace", "Mine 3 iron ore", "Smelt 3 iron ore", "Craft 1 iron pickaxe", "Mine 1 diamond". A manual curriculum requires human effort to design and is not scalable for open-ended exploration.
- **Random Curriculum**: We curate 101 items obtained by VOYAGER and create a random curriculum by randomly selecting one item as the next task.
- **w/o Skill Library**: We remove the skill library, eliminating skill retrieval for code generation.
- **w/o Environment Feedback**: We exclude environment feedback (chat log) from the prompt for code generation.
- **w/o Execution Errors**: We exclude execution errors from the prompt for code generation.
- **w/o Self-Verification**: For each task, we generate code without self-verification and iteratively refine the program for 3 rounds (equivalent to 4 rounds of code generation in total).
- **GPT-3.5**: We replace GPT-4 with GPT-3.5 for code generation. We retain GPT-4 for the automatic curriculum and the self-verification module.

B.4 Evaluation Results

B.4.1 Significantly Better Exploration

The meaning of each icon in Fig. 1 is shown in Fig. A.1.

We run three trials for each method. The items collected by VOYAGER in each trial is

- **Trial 1**: 'iron_ingot', 'stone_shovel', 'iron_leggings', 'fishing_rod', 'pufferfish', 'oak_log', 'cooked_mutton', 'green_dye', 'flint', 'chest', 'iron_sword', 'string', 'ender_pearl', 'raw_copper', 'crafting_table', 'cactus', 'lapis_lazuli', 'iron_pickaxe', 'copper_ingot', 'stone_pickaxe', 'wooden_hoe', 'scaffolding', 'stick', 'porkchop', 'copper_block', 'gravel', 'grass_block', 'white_bed', 'bone', 'dirt', 'mutton', 'white_wool', 'oak_sapling', 'coal', 'bamboo', 'wooden_pickaxe', 'rotten_flesh', 'cooked_porkchop', 'cod', 'iron_boots', 'lightning_rod', 'diorite', 'water_bucket', 'shears', 'furnace', 'andesite', 'granite', 'bucket', 'wooden_sword', 'sandstone', 'iron_helmet', 'raw_iron', 'sand', 'acacia_log', 'cooked_cod', 'oak_planks', 'azure_bluet', 'iron_shovel', 'acacia_planks', 'shield', 'iron_axe', 'iron_chestplate', 'cobblestone';
- **Trial 2**: 'iron_ingot', 'tuff', 'stone_shovel', 'iron_leggings', 'fishing_rod', 'cooked_mutton', 'spruce_planks', 'gunpowder', 'amethyst_shard', 'chest', 'string', 'cooked_salmon', 'iron_sword', 'raw_copper', 'crafting_table', 'torch', 'lapis_lazuli', 'iron_pickaxe', 'copper_ingot', 'stone_pickaxe', 'wooden_hoe', 'stick', 'amethyst_block', 'salmon', 'calcite', 'gravel', 'white_bed', 'bone', 'dirt', 'mutton', 'white_wool', 'spyglass', 'coal', 'wooden_pickaxe', 'cod', 'iron_boots', 'lily_pad', 'cobbled_deepslate', 'lightning_rod', 'snowball', 'stone_axe', 'smooth_basalt', 'diorite', 'water_bucket', 'furnace', 'andesite', 'bucket', 'granite', 'shield', 'iron_helmet', 'raw_iron', 'cobblestone', 'spruce_log', 'cooked_cod', 'tripwire_hook', 'stone_hoe', 'iron_chestplate', 'stone_sword';
- **Trial 3**: 'spruce_planks', 'dirt', 'shield', 'redstone', 'clock', 'diamond_sword', 'iron_chestplate', 'stone_pickaxe', 'leather', 'string', 'chicken', 'chest', 'diorite', 'iron_leggings', 'black_wool', 'cobblestone_wall', 'cobblestone', 'cooked_chicken', 'feather', 'stone_sword', 'raw_gold', 'gravel', 'birch_planks', 'coal', 'cobbled_deepslate', 'oak_planks', 'iron_pickaxe', 'granite', 'tuff', 'crafting_table', 'iron_helmet', 'stone_hoe', 'iron_ingot', 'stone_axe', 'birch_boat', 'stick', 'sand', 'bone', 'raw_iron', 'beef', 'rail', 'oak_sapling', 'kelp', 'gold_ingot', 'birch_log', 'wheat_seeds', 'cooked_mutton', 'furnace', 'arrow', 'stone_shovel', 'white_wool', 'andesite', 'jungle_slab', 'mutton', 'iron_sword', 'copper_ingot', 'diamond', 'torch', 'oak_log', 'cooked_beef', 'copper_block', 'flint', 'bone_meal', 'raw_copper', 'wooden_pickaxe', 'iron_boots', 'wooden_sword'.

The items collected by ReAct [29] in each trial is

- **Trial 1**: 'bamboo', 'dirt', 'sand', 'wheat_seeds';
- **Trial 2**: 'dirt', 'rabbit', 'spruce_log', 'spruce_sapling';
- **Trial 3**: 'dirt', 'pointed_dripstone';

The items collected by Reflexion [30] in each trial is

- **Trial 1**: 'crafting_table', 'orange_tulip', 'oak_planks', 'oak_log', 'dirt';
- **Trial 2**: 'spruce_log', 'dirt', 'clay_ball', 'sand', 'gravel';
- **Trial 3**: 'wheat_seeds', 'oak_log', 'dirt', 'birch_log', 'sand'.

The items collected by AutoGPT [28] in each trial is

- **Trial 1**: 'feather', 'oak_log', 'leather', 'stick', 'porkchop', 'chicken', 'crafting_table', 'wheat_seeds', 'oak_planks', 'dirt', 'mutton';
- **Trial 2**: 'wooden_pickaxe', 'iron_ingot', 'stone', 'coal', 'spruce_planks', 'string', 'raw_copper', 'crafting_table', 'diorite', 'andesite', 'furnace', 'torch', 'spruce_sapling', 'granite', 'iron_pickaxe', 'stone_pickaxe', 'wooden_axe', 'raw_iron', 'stick', 'spruce_log', 'dirt', 'cobblestone';
- **Trial 3**: 'wooden_shovel', 'wooden_pickaxe', 'iron_ingot', 'stone', 'cod', 'coal', 'oak_log', 'flint', 'raw_copper', 'crafting_table', 'diorite', 'furnace', 'andesite', 'torch', 'granite', 'lapis_lazuli', 'iron_pickaxe', 'stone_pickaxe', 'raw_iron', 'stick', 'gravel', 'oak_planks', 'dirt', 'iron_axe', 'cobblestone'.

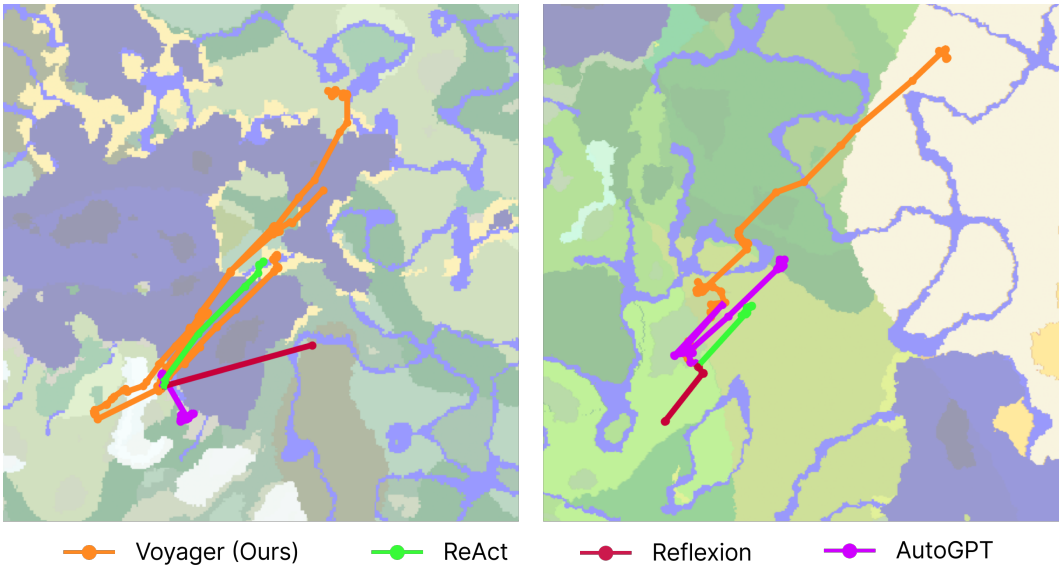

Figure A.2: Map coverage: Two bird's eye views of Minecraft maps. VOYAGER is able to traverse 2.3× longer distances compared to baselines while crossing diverse terrains. Trajectories are plotted based on the positions where each agent interacts with GPT-4.

B.4.2 Extensive Map Traversal

Agent trajectories for map coverage are displayed in Fig. A.2. Fig. 7 is plotted based on Fig. A.2 by drawing the smallest circle enclosing each trajectory. The terrains traversed by VOYAGER in each trial is

- **Trial 1**: 'meadow', 'desert', 'river', 'savanna', 'forest', 'plains', 'bamboo_jungle', 'dripstone_caves';
- **Trial 2**: 'snowy_plains', 'frozen_river', 'dripstone_caves', 'snowy_taiga', 'beach';
- **Trial 3**: 'flower_forest', 'meadow', 'old_growth_birch_forest', 'snowy_slopes', 'frozen_peaks', 'forest', 'river', 'beach', 'ocean', 'sunflower_plains', 'plains', 'stony_shore'.

The terrains traversed by ReAct [29] in each trial is

- **Trial 1**: 'plains', 'desert', 'jungle';
- **Trial 2**: 'snowy_plains', 'snowy_taiga', 'snowy_slopes';
- **Trial 3**: 'dark_forest', 'dripstone_caves', 'grove', 'jagged_peaks'.

The terrains traversed by Reflexion [30] in each trial is

- **Trial 1**: 'plains', 'flower_forest';
- **Trial 2**: 'snowy_taiga';
- **Trial 3**: 'old_growth_birch_forest', 'river', 'ocean', 'beach', 'plains'.

The terrains traversed by AutoGPT [28] in each trial is

- **Trial 1**: 'plains', 'dripstone_caves', 'savanna', 'meadow';
- **Trial 2**: 'snowy_taiga';
- **Trial 3**: 'plains', 'stony_shore', 'forest', 'ocean'.

B.4.3 Efficient Zero-Shot Generalization to Unseen Tasks

The results of zero-shot generalization to unseen tasks for the other two tasks are presented in Fig. A.3. Similar to Fig. 8, VOYAGER consistently solves all tasks, while the baselines are unable to solve any

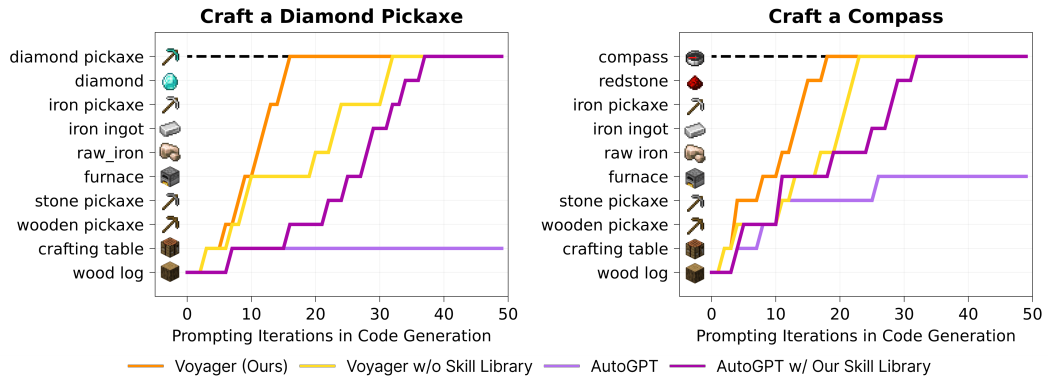

Figure A.3: Zero-shot generalization to unseen tasks. We visualize the intermediate progress of each method on the other two tasks. We do not plot ReAct and Reflexion since they do not make any meaningful progress.

task within 50 prompting iterations. Our skill library, constructed from lifelong learning, not only enhances VOYAGER's performance but also provides a boost to AutoGPT [28].

B.4.4 Multimodal Feedback from Humans

VOYAGER does not currently support visual perception, because the available version of GPT-4 is text-only at the time of this writing. However, VOYAGER has the potential to be augmented by multimodal perception models [59, 58] to achieve more impressive tasks. We demonstrate that given human feedback, VOYAGER is able to construct complex 3D structures in Minecraft, such as a Nether Portal and a house (Fig. 10). There are two ways to integrate human feedback:

(1) Human as a critic (equivalent to VOYAGER's self-verification module): humans provide visual critique to VOYAGER, allowing it to modify the code from the previous round. This feedback is essential for correcting certain errors in the spatial details of a 3D structure that VOYAGER cannot perceive directly.

(2) Human as a curriculum (equivalent to VOYAGER's automatic curriculum module): humans break down a complex building task into smaller steps, guiding VOYAGER to complete them incrementally. This approach improves VOYAGER's ability to handle more sophisticated 3D construction tasks.

B.4.5 Accurate Skill Retrieval

We conduct an evaluation of our skill retrieval (309 samples in total) and the results are in Table. A.4. The top-5 accuracy standing at 96.5% suggests our retrieval process is reliable (note that we include the top-5 relevant skills in the prompt for synthesizing a new skill).

Table A.4: Skill retrieval accuracy.

Top-1 Acc	Top-2 Acc	Top-3 Acc	Top-4 Acc	Top-5 Acc
80.2 ± 3.0	89.3 ± 1.8	93.2 ± 0.7	95.2 ± 1.8	96.5 ± 0.3

B.4.6 Robust to Model Variations

In the main paper, all of Voyager's experiments are conducted with `gpt-4-0314`. We additionally run new experiments with `gpt-4-0613` and find that the performance is roughly the same (Fig. A.4). It demonstrates that Voyager is robust to model variations.

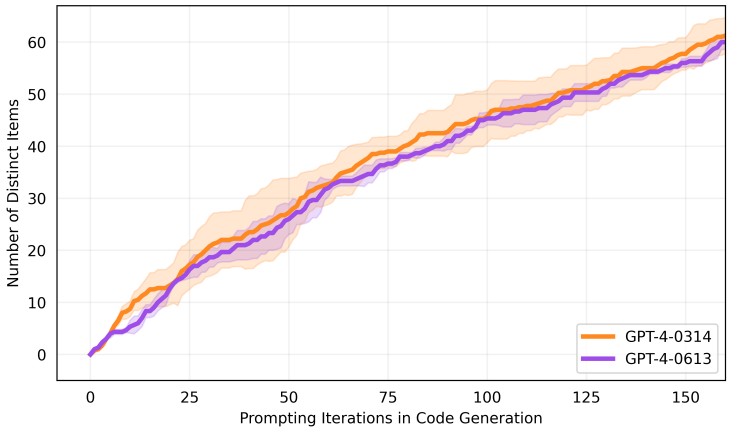

Figure A.4: VOYAGER's performance with GPT-4-0314 and GPT-4-0613.

C Broader Impacts

Our research is conducted within Minecraft, a safe and harmless 3D video game environment. While VOYAGER is designed to be generally applicable to other domains, such as robotics, its application to physical robots would require additional attention and the implementation of safety constraints by humans to ensure responsible and secure deployment.