

# LLMR: Real-time Prompting of Interactive Worlds using Large Language Models

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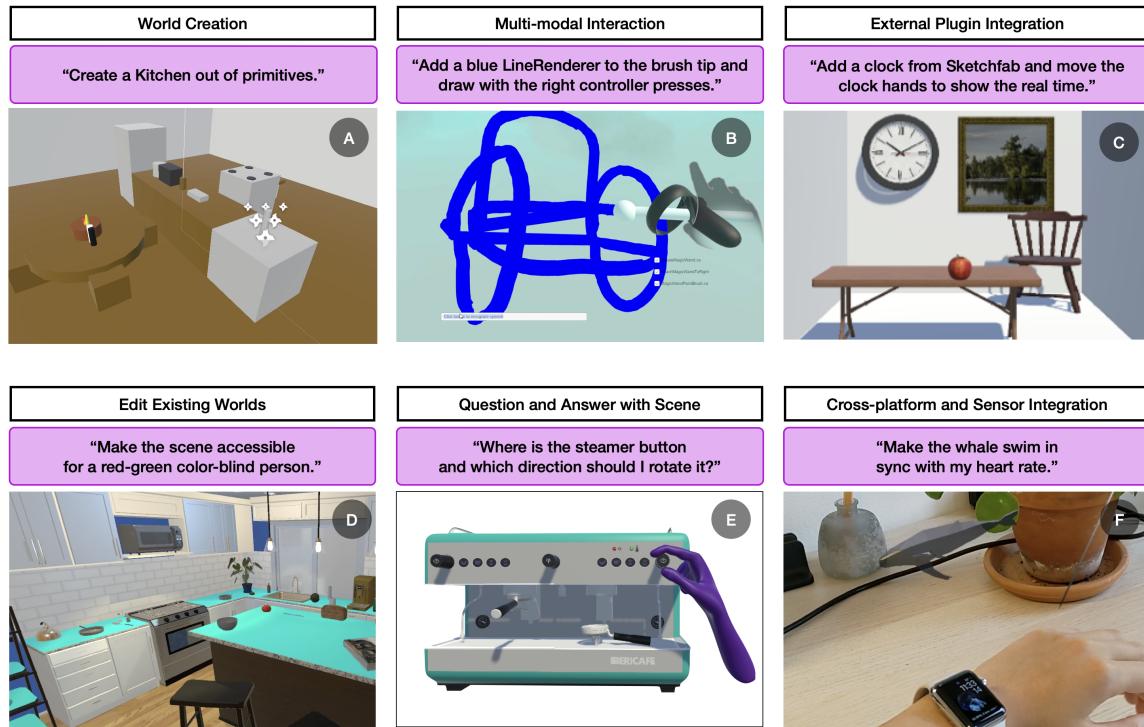


Fig. 1. Examples of diverse use cases and functionalities enabled by Large Language Model for Mixed Reality (LLMR). A: Creation of a kitchen scene from scratch using Unity primitives. B: Prompting and drawing objects into existence via multi-modal interactions. C: Integration with external plugins like SketchFab to create high-fidelity scenes and prompting skills like animation creation. D: Edit existing VR scenes. E: Automated generation of instructional guides and QA with scene knowledge. F: Cross-platform compatibility and external sensor integration.

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We present Large Language Model for Mixed Reality (LLMR), a framework for the real-time creation and modification of interactive Mixed Reality experiences using LLMs. LLMR leverages novel strategies to tackle difficult cases where ideal training data is scarce, or where the design goal requires the synthesis of internal dynamics, intuitive analysis, or advanced interactivity. Our framework relies on text interaction and the Unity game engine. By incorporating techniques for scene understanding, task planning, self-debugging, and memory management, LLMR outperforms the standard GPT-4 by 4x in average error rate. We demonstrate LLMR's cross-platform interoperability with several example worlds, and evaluate it on a variety of creation and modification tasks to show that it can produce and edit diverse objects, tools, and scenes. Finally, we conducted a usability study (N=11) with a diverse set that revealed participants had positive experiences with the system and would use it again.

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## 1 INTRODUCTION

Creating 3D virtual worlds is a challenging task that requires both artistic and technical skills. In addition, 3D content often becomes deprecated and has limited interoperability due to platform and device upgrades. Recently, generative AI models have made considerable progress in producing meshes for objects and scenes [17, 18, 21, 24, 25, 39, 41]. However, few works have ventured beyond visual appearances to bring e.g., interactive and behavioral elements into the generated content. In addition, existing rendering-based methods require substantial compute and time to generate and render 3D objects, while the quality and resolution of these generations are limited [11, 33].

On the other hand, the rapid advancement in Large Language Models (LLM) like GPT has shown promise in code generation and reasoning [1, 6, 14, 20, 31]. An integration of LLMs with a game engine, like Unity [48], can enable faster 3D content development and spontaneous user creation, a core element of mixed reality since its inception. In addition, the 3D mixed reality worlds offer rich, spatial, multimodal information (most are post-symbolic or beyond language) that can potentially help LLMs to better situate their reasoning in the reality that humans live in.

This paper presents **LLMR**(Large Language Models for Mixed Reality), a framework that enables real-time creation and modification of interactive 3D scenes. LLMR can create objects that are rich in both visual and behavioral aspects, or make spontaneous and bespoke edits on an existing environment. For example, we leverage LLMR to spawn interactive tools that are self-contained units designed to perform specific functions in virtual and mixed-reality environments. They can be combined to form more complex interactive systems, extending the range and depth of user and AI-driven experiences. These configurations can be saved and transferred across various environments, serving as the building blocks for versatile interactive experiences.

LLMR is an orchestration of an ensemble of specialized GPTs. At its center is the *Builder* GPT serving as an architect of C# Unity code for crafting interactive scenes. However, the multitude of tasks falling under virtual world creation renders a standalone coder insufficient. For instance, the ability to meaningfully modify an existing virtual world necessitates a profound semantic understanding of the scene. As humans, we have the ability to infer the properties of objects in the world and can refer to objects in the environment using demonstratives. To simulate the benefits of

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perceptual access, we incorporated the *Scene Analyzer GPT*. It generates a comprehensive summary of scene objects, offering detailed information when requested, including aspects like size, color, and the functionalities of interactive tools previously generated by LLMR. We also implemented the *Skill Library GPT* that determines the relevant skills that are needed for the *Builder* to accomplish the user’s request. In addition, we have observed that the code generated by the *Builder* lacks robustness and frequently contains bugs. To remedy this, we introduce the *Inspector GPT*, which evaluates the *Builder*’s code against a predefined set of rules. This evaluation acts as a protective measure against compilation and run-time errors before the code is executed via the *Compiler*.

To illustrate the efficacy of our framework in the creation and editing of virtual scenes, we tested LLMR on two sets of 150 prompts encompassing a wide array of creation and modification tasks. Our findings demonstrate LLMR’s superior performance in contrast to general-purpose LLMs while emphasizing the performance gain achieved with the addition of each module in our pipeline. In particular, LLMR exhibits over 3x reduction in code errors in both an empty and an existing scene, when compared to off-the-shelf GPT-4 [32]. This outcome underscores LLMR’s capacity to execute user instructions with a higher degree of robustness.

To evaluate if our framework is able to generate not only functional code but also interactive worlds that meet users’ instructions, we evaluated LLMR with 11 participants with varying Unity experiences. At a high level, participants found LLMR to be intuitive and easy to use, and they were able to iteratively achieve desired outputs without much manual scripting. While the framework has limitations such as its unpredictability due to generative models’ stochastic nature, and thus is not applicable for all contexts (especially ones that require precise and specific control), the output generated by LLMR serves as a starting point for more complex scene generation. In summary, our three main contributions are the following:

- (1) We introduced a versatile framework for real-time generation of interactive 3D objects and scenes using LLM modules, designed for easy setup with an OpenAI API key and adaptable across various mixed reality tools, environments, and devices.
- (2) We carried out extensive evaluations, including a technical ablation study to gauge the framework’s performance and reliability, and a user study to derive design recommendations for optimizing the user experience.
- (3) We showcased the expanded capabilities of GPT beyond text inputs, illuminating the broader potential of LLM applications, and demonstrated the framework’s broad applicability in domains such as remote training, creativity, and accessibility.

## 2 RELATED WORK

Our research on the creation and modification of interactive 3D scenes using natural language is situated at the intersection of large language models (LLMs) and 3D content generation. This section provides an overview of the related work in these areas, highlighting how our work builds upon and extends existing research.

### 2.1 Generative 3D Assets

The generation of 3D assets has been a significant focus in recent research. The work of Li et al. with 3DDesigner [24], Jun and Nichol with Shap-E [21], and Poole et al. with DreamFusion [33] have demonstrated the potential of text guidance and generative models in creating complex and diverse 3D objects. Lin et al. introduce Magic3D [25], a high-resolution text-to-3D content creation framework that addresses the limitations of slow optimization and low-resolution output inherent in existing methods like DreamFusion. Recently, Holodiffusion by Karnewar et al.

[22] furthered the conversation by employing diffusion models for 3D generative modeling. The Instruct-NeRF2NeRF method [15] and advancements like Pointclip v2 [61] as well as the work of Roberts et al. [37] have explored the power of prompting techniques in 3D open-world learning. Our approach extends beyond visual appearances to incorporate interactive and behavioral elements into the generated content.

## 2.2 Interactive 3D Environments

Recently, the creation of interactive 3D environments has been further explored, with contributions from Wang et al. with Voyager [51], Singer et al. with MAV3D [39], and Höllerin, Lukas, et al. with Text2Room [17]. Volum et al. has shown that LLMs can be used to guide NPC interactions with a virtual environment [50]. Wang et al. also introduced Chat-3D [54], a system that focuses on universal dialogues for 3D scenes, which is further augmented by the work of Hong et al. with 3D-LLM [18]. New approaches like Oasis [41] and Procedurally Generated Virtual Reality [42] add novel perspectives. Thoravi Kumaravel et al. [49] complement these efforts by focusing on bi-directional mixed-reality telepresence. While these contributions are significant in building interactive 3D spaces, the interplay between AI and mixed reality in these environments remains an open question. Our work tackles this gap by bringing the capabilities of LLMs to a real-time Unity editor for Mixed Reality applications.

## 2.3 Editor Support for Mixed Reality Development

Mixed Reality (XR) development has been explored by Hirzle et al. [16] and Fidalgo et al. [9], who provide comprehensive reviews at the intersection of AI and XR. Lindlbauer et al. [26] and Cheng et al. [5] focus on the automatic adaptation of MR interfaces, a line of work that is relevant for multi-user XR experiences, as shown by Mandi et al. with RoCo [28].

## 2.4 Procedural Generation and Object Compositing

Research by Freiknecht and Effelsberg [10], Cao et al. [4], and Song et al. [40] has focused on the balance between realism and algorithmic performance. Recent advancements such as Interactive Example-Based Terrain Authoring with Conditional Generative Adversarial Networks by Guérin et al. [13] add a layer of complexity in how terrains can be generated from simple user inputs. DeepSpace introduced a novel method of mood-based texture generation from music [43], adding another layer of complexity to asset generation. Daffara et al. [7] and Rana et al. [35] further extended these concepts to include demonstrations and task planning.

## 2.5 Interpreting Non-Linguistic Information

Lastly, the work of Zhang et al. with MotionGPT [58], Wu et al.'s work on Embodied Task Planning [55] as well as Richardson et al. with TEXTure [36], and Driess et al. with PaLM-E [8] has shown the potential of LLMs in generating human motion, texturing 3D shapes, and incorporating real-world sensor modalities, respectively. These efforts are complemented by Xu et al. with XAIR [56], which focuses on explainable AI in augmented reality. A comprehensive review of Neural Radiance Field (NeRF) models by Gao et al. [11] adds to our understanding of this rapidly growing field and aligns with our approach of enabling LLMs to interpret non-linguistic or non-symbolic information.

## 3 LLMR: A FRAMEWORK FOR GENERATING REAL-TIME, INTERACTIVE 3D WORLDS USING LARGE LANGUAGE MODELS

Large language models are capable code generators, and their ability to synthesize programs have been extensively tested [1, 6, 14, 20, 31]. Scripting in a game engine, however, is especially challenging given the multitude of tasks

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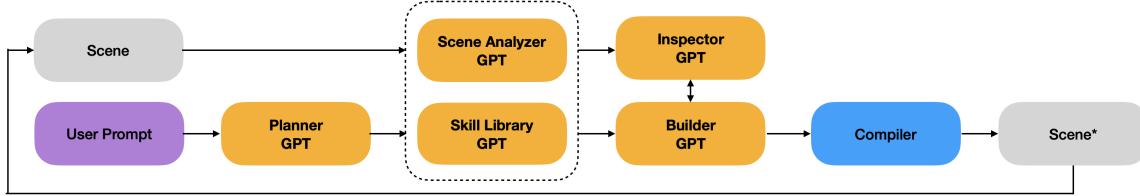


Fig. 2. *Large Language Model for Mixed Reality (LLMR)* architecture for real-time interactive 3D scene generation. Starting from the left, a user prompt and the existing 3D scene ( $\Omega$ ) are fed into the *Planner* and *Scene Analyzer* (SA) modules, respectively. The *Planner* decomposes the user prompt into a sequence of sub-prompts, while the SA summarizes the current scene elements. These are then integrated with a *Skill Library* (SL) to guide the *Builder* module, which generates the appropriate code. The *Inspector* module iteratively checks the generated code for compilation and run-time errors. Upon receiving the green light from the *Inspector*, the code is compiled using the Roslyn Compiler and executed in the Unity Engine to produce the desired 3D scene and functionalities as specified by the user.

and the complexity of the development environment. For a non-comprehensive list, generating a realistic 3D world may involve object creation, texturing, behavior programming, event scripting, animations, particle effects, lighting, and user interface [3]. Prompting these elements in real-time requires a framework that understands the virtual scene, interprets user intention, and generates high-quality code. To this end, we present Large Language Model for Mixed Reality (LLMR), a framework that enables real-time creation and modification of interactive 3D scenes using natural language.

LLMR is an orchestration of language models, each contextualized with a distinct metaprompt to outline its role, as illustrated in Figure 2. A metaprompt is a specially crafted input sequence or context that guides an LLM’s behavior or output, enabling more focused or nuanced responses than standard prompts. We start with the *Planner*, which breaks down the user’s request into a sequence of appropriately scoped instructions. These instructions, along with a concise summary of the existing scene and extra knowledge for specialized skills, are used as inputs to the central module called *Builder*, which generates code to fulfill these instructions. In addition, we use a separate *Inspector* module to check the *Builder*’s generated code against potential compilation and run-time errors before finally executing the code. Below, we detail each module and explain the design choices that enable various aspects of prompting a virtual world into existence.

The task of generating interactive 3D scenes boils down to generating and executing appropriate code snippets to accomplish the user’s prompt. Formally, denote the user’s request by  $u$  and the current 3D world by  $\Omega$  (which may be empty), we wish to draw sample  $x \sim \mathcal{P}(x|u, \Omega)$ , where  $\mathcal{P}$  is the distribution of syntactically valid, request-fulfilling code. We then compile and execute  $x$  at run-time under the Unity Engine [48], a development platform for creating virtual scenes that suits our needs.

### 3.1 Planner

Prompting a world into existence can be a hefty task. “Create a city and all its denizens” is a valid request, albeit one that is overly ambitious to achieve in a single step. Following the common wisdom “nothing is particularly hard if broken into small jobs”, instead of directly sampling from  $\mathcal{P}(x|u, \Omega)$ , we propose a *Planner*  $P : u \mapsto (u_1, u_2, \dots, u_N)$  to decompose each prompt into subtasks within an appropriate scope, then use autoregressive sampling to carry out these

**Algorithm 1** LLMR

**Require:**  $u$ : user's request;  $\Omega$  : current scene;  $A(s|u, \Omega)$ : Scene Analyzer;  $P(u_1, \dots, u_N|u, s)$ : Planner;  $L(h|u)$ : Skill Library;  $B(x|u, s, h)$  : Builder;  $I(r, v|u, s, x)$ : Inspector.

```

1:  $s \sim A(\cdot|u, \Omega)$ 
2:  $(u_1, \dots, u_N) \sim P(\cdot|u, s)$                                 ▷ Decomposes the request into suitable instructions.
3: for  $i = 1 : N$  do
4:    $s_i \sim A(\cdot|u_i, \Omega_i)$                                      ▷ Analyze the current scene.
5:    $h_i \sim L(\cdot|u_i)$                                          ▷ Retrieve required skills, if any.
6:    $x_i \leftarrow \text{GenerateCodeWithInspection}(u_i, s_i, h_i)$     ▷ Generate verified code per the instruction.
7:    $\Omega_i \leftarrow \text{CompileAndRun}(x_i)$                            ▷ Execute the code to change the world state.
8: end for

```

subtasks via a sequence of generated code ( $x_1, x_2, \dots, x_N$ ):

$$\begin{aligned} \mathcal{P}(x_1, x_2, \dots, x_N|u_1, u_2, \dots, u_N, \Omega) &= \mathcal{P}(x_1|u_1, u_2, \dots, u_N, \Omega) \prod_{n=1}^{N-1} \mathcal{P}(x_{n+1}|x^n, u_1, u_2, \dots, u_N, \Omega) \\ &= \mathcal{P}(x_1|u_1, \Omega) \prod_{n=1}^{N-1} \mathcal{P}(x_{n+1}|x^n, u_{n+1}, \Omega) \end{aligned} \quad (1)$$

where  $x^n := (x_1, \dots, x_n)$ . The second quality follows by assuming independence of code generations and requests at different steps,  $x_n \perp\!\!\!\perp u_m, \forall m \neq n$ . An illustration for this procedure is provided in Figure 3. However, sampling from  $\mathcal{P}(x_{n+1}|x^n, u_{n+1}, \Omega)$  may be difficult for a language model, because it has to *infer* the effect of  $(x_1, \dots, x_n)$  on the initial

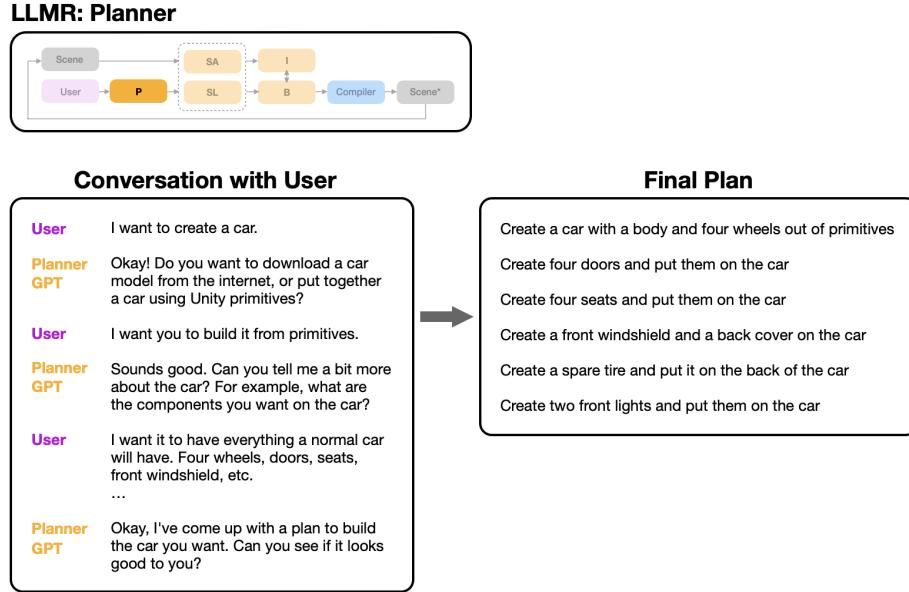


Fig. 3. The Planner and its role in breaking down a user's high-level request into a sequence of manageable subtasks ( $u_1, u_2, \dots, u_n$ ). The Planner engages in a user-oriented conversation to determine the appropriate scope and granularity of each subtask. Following this, the Builder executes the plan by generating code ( $x_1, x_2, \dots, x_n$ ) for each subtask, effectively carrying out the user's initial request.

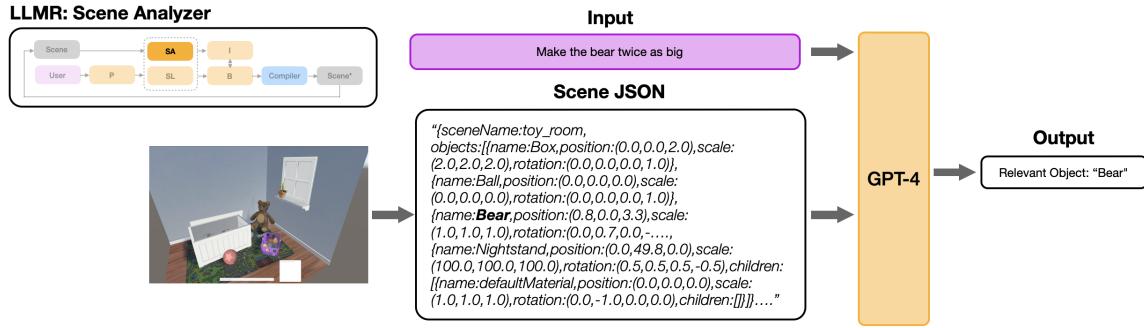


Fig. 4. *Scene Analyzer module*. The virtual scene, depicted in the bottom-left corner, is converted into a parsed scene hierarchy in JSON format. This, along with the user request, serves as input to the Scene Analyzer. The output is a filtered, relevant summary of the scene, which is then used for conditioning subsequent modules like the Builder. The process optimizes the utilization of the language model’s fixed context window and enhances focus on objects relevant to the user prompt.

world  $\Omega$  before writing code  $x_{n+1}$ . To remove the guesswork, we leverage a runtime compiler  $R$  to execute  $(x_1, \dots, x_n)$  in order, each time getting a new world state  $\Omega_{n+1} = R(x_{n+1}, \Omega_n)$ . We can then rewrite:

$$\mathcal{P}(x_{n+1}|x^n, u_{n+1}, \Omega) = \mathcal{P}(x_{n+1}|x_n, u_{n+1}, \Omega_n), \quad (2)$$

where we assume  $\{x_i\}_{i=1}^n$  is Markovian when conditioned on  $\Omega_n$ . That is, the current world state is rich enough to capture all previous executions past the most recent one.

In principle, it is possible for the user to limit their prompts within a certain difficulty so that the decomposition is unnecessary. However, the user may not know the appropriate task scope a priori (if creating a city is too hard, how about a single house? Or a room in the house?) As a result, having a properly configured Planner makes the framework robust to prompts of varying difficulty. In addition, the user may have different levels of details in their prompt. For example, "Creating a car" is a valid request that nevertheless does not specify its appearance or functionality. Here, the Planner serves as a conversational assistant that interacts with the user to devise a plan with an appropriate scope and granularity, which significantly improves the user experience.

### 3.2 Scene Analyzer

There are many possible representations for a virtual world  $\Omega$  that may include visual, behavioral, and auditory elements. In this work, we derive  $\Omega$  from the Unity scene hierarchy, which contains all existing game objects, their attached components, and their parent-child relations. The hierarchy is parsed into a JSON string and can then be used as input to language models. However, directly using the raw JSON string as input proves to be infeasible in practice. First, most prompts only require interactions with a small subset of  $\Omega$ , so it is unnecessary and even distracting to use its entirety as input. Second, LLMs have a fixed context window  $W$  that serves as its short-term memory, which has to contain its metaprompt, few-shot examples, user prompt, and generative output [59]. For example, GPT-4 supports either 8k or 32k tokens for maximum number of token at a time[32], but even the 32k token limit can be insufficient, particularly for intricate scenes containing numerous objects, each consisting of multiple components.

To tackle these issues, we created a separate module termed the *Scene Analyzer*, which is a properly prompted LLM  $A(s|u, \Omega)$  that outputs a succinct summary of  $\Omega$  conditional on the user request. On a high level, one can think of the

Scene Analyzer as a means of perception that relays an abstraction of the environment for downstream processing. An illustration of the module is provided in Figure 4. Concretely, the output  $s_n \sim A(\cdot|u, \Omega_n)$  is used to reparametrize the density at each sampling step:

$$\mathcal{P}(x_{n+1}|x_n, u_{n+1}, s_n) \sim \mathcal{P}(x_{n+1}|x_n, u_{n+1}, \Omega_n) \quad (3)$$

### 3.3 Builder-Inspector

Central to LLMR is the *Builder*  $B(x|u, s)$ , a module responsible for generating code conditional on the user prompt. It serves as our main apparatus for approximating  $\mathcal{P}$ . In other words, we hope

$$B(x|x_n, u_{n+1}, s_n) \approx \mathcal{P}(x_{n+1}|x_n, u_{n+1}, s_n), \quad (4)$$

holds with a carefully crafted metaprompt and enough in-context demonstrations. In practice, however, the complex nature of creating a virtual world makes the approximation unsatisfactory even with as many examples as the context length allows. This is largely because the Builder module is asked to accomplish the instructions with some creativity while faithfully following an extensive list of specific guidelines that align the output, which causes to Builder to have a "cognitive overload".

To ameliorate this, we introduce another module, the *Inspector*  $I(r, v|x, s)$ , that checks the Builder's generated code for compilation and run-time errors. In the case of a failed inspection indicated by verdict  $v$ , the Inspector outputs a suggestion  $r$  for potential fixes and prompts the Builder to make another attempt. As a result, the Builder and Inspector works in tandem to write and self-debug code, forming a feedback system that significantly improves the quality of the generated scripts. We outline this paradigm in Algorithm 2 and illustrate it in Figure 5. Interestingly, the Inspector excels at catching errors even if the same guidelines in its metaprompt are present in the Builder. One possibility is that this is due to providing a more extensive list of negative and positive examples to the *Inspector*. Still, when the *Builder*

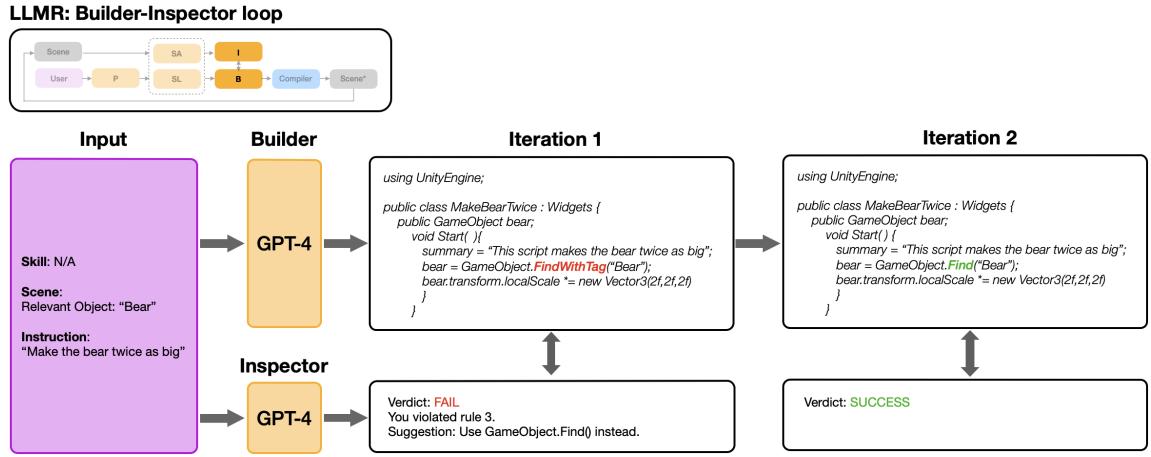


Fig. 5. *Builder-Inspector paradigm in LLMR*. The Builder module  $B(x|u, s)$  generates code based on user input and current state. The generated code is then inspected by the Inspector module  $I(r, v|x, s)$  for compilation and run-time errors. If errors are found, indicated by verdict  $v$ , the Inspector provides suggestions  $r$  for corrections. The process iterates until either the code passes inspection or a maximum number of inspections  $T$  is reached. This feedback loop significantly enhances the quality of the generated scripts.

is provided with the same examples, performance is not as high. Our intuition for this is that verifying a snippet of code is easier than writing the said code, or the two tasks bear different failure modes that can be effectively hedged.

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**Algorithm 2** Generate Code With Inspection
 

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**Require:**  $u$ : user's request,  $s$ : scene summary,  $h$ : additional hint.  $B(x|u, s, h)$  : Builder;  $I(r, v|u, s, x)$ : Inspector;  $T$ : maximum number of inspections.

```

1:  $t \leftarrow 0$                                 ▷ Initialization
2:  $r_0 \leftarrow \emptyset$ 
3:  $v_0 \leftarrow \text{False}$ 
4: while  $t < T$  and  $v_t$  is false do
5:    $x_t \sim B(\cdot|u, s, h, r_t)$                 ▷ Builder writes code  $x_t$ 
6:    $(r_t, v_t) \sim I(\cdot|s, x)$                   ▷ Inspector checks code, outputs verdict  $v_t$  and suggestion  $r_t$ 
7:    $t \leftarrow t + 1$ 
8: end while
9: return  $x$ 
  
```

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### 3.4 Compilation, Save and Reload

After the Builder-generated script passes the inspection, we follow the approach in [37] to compile and execute the scripts at runtime through the Roslyn C# compiler [47]. The inclusion of run-time compilation elevates LLMR from an offline development tool to a real-time generative framework.

To enable iterative design, users can save their generations and selectively reload the saved generations in the existing or new scene without having to repeat the prompting process. The generated output is saved as C# scripts and reattached to the Compiler to be compiled at runtime. A one-sentence summary of each script's function is saved, so alternatively, the output can also be regenerated by the framework based on the summary.

### 3.5 Skill Library

The creation of the *Skill Library* Module is motivated by two primary challenges. The first is the token size limitation imposed by the GPT architecture on the context, or "metaprompt," provided to the *Builder*. Typically, the *Builder* is presented with a comprehensive list of various APIs and plug-ins that could be employed to meet the user's needs. As the range of available skills expands, this list lengthens, eventually surpassing GPT's token size limit for public users.

The second challenge lies in the *Builder*'s attention capacity, which appears to be limited. Even when we attempt to condense all the available skills into the *Builder*'s metaprompt, it struggles to keep track of a specific skill when the list becomes too lengthy. This limitation is further exacerbated by the necessity to include precise coding examples for each plug-in to ensure their effective utilization by GPT.

To address these challenges, we created the *Skill Library* module, denoted as  $L(h|u)$ , which serves as a centralized repository for all available skills and as an attention mechanism that retrieves only the skills relevant to a specific user prompt.

Formally, a specialized GPT is provided with a metaprompt containing two essential pieces of information: 1) a high-level summary of the available skills, and 2) the user's prompt. The GPT model is tasked with identifying either a single skill or a subset of skills that are most pertinent to the user's request. The *Skill Library* remains efficient and small in token size because it only needs the high-level descriptions of each skill, while the specific usage details, as well as

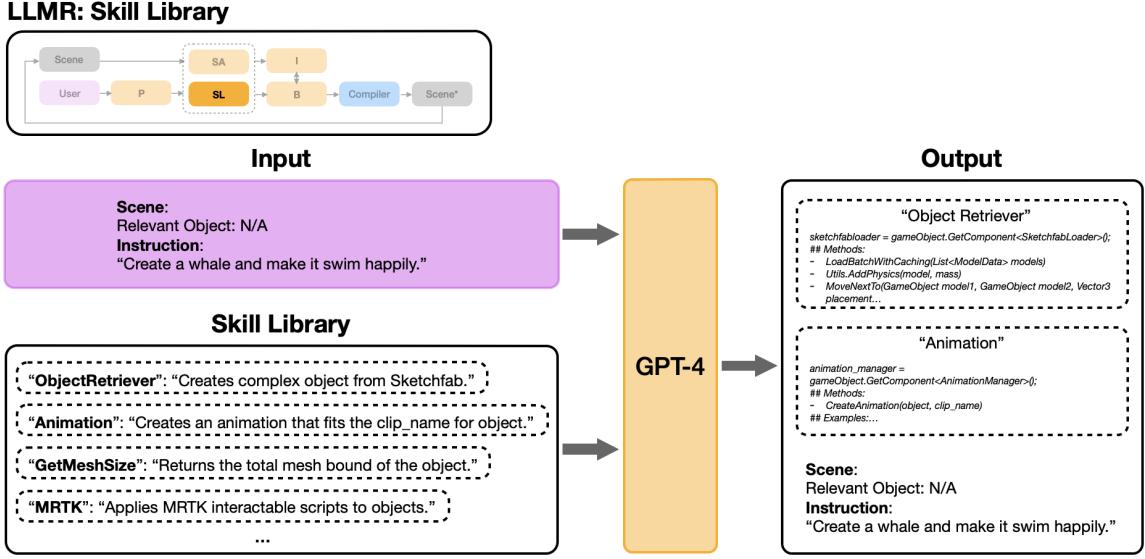


Fig. 6. *Skill Library module workflow*. On the left, the module receives inputs from the Scene Analyzer and a user prompt "create a whale and make it swim happily". A list of skills is provided to the SL GPT module in its metaprompt, which also contains a high-level summary of available skills such as object retrieval and animation. The module then identifies and outputs the most relevant skills (in this case, object retriever and animation) to the *Builder*, which subsequently utilizes these tools for implementation.

positive and negative examples, are stored separately. Once the relevant skills are identified, their detailed information and usage examples are fetched and passed on to the *Builder* for implementation.

$$h_i \sim L(\cdot|u_i) \quad (\text{Retrieve required skills, if any.}) \quad (5)$$

As an illustrative example, consider a skill we created for GPT's use, which leverages a combination of generative and contrastive models along with the Sketchfab API to source and integrate 3D models into a scene. While we delve into the specifics of this skill in the next section, it is worth noting that the *Skill Library* only receives a high-level summary of how this particular skill functions, along with similar descriptors for other skills. The actual examples needed to use this skill are then retrieved and supplied to the *Builder* for execution.

$$B(x|u, s, h) : \text{Builder}; \text{ where } h = \text{retrieved skills from } L \quad (6)$$

This approach ensures that the Skill Library and the Builder work in tandem to efficiently and effectively generate code that fulfills the user's request, while overcoming the token size and attention capacity limitations of LLMs.

#### 4 INCORPORATING EXISTING OPEN-SOURCE 3D ASSETS

The process of generating interactive 3D scenes often involves the creation and placement of various objects. For instance, a request to create an office space might be decomposed into the generation of a desk, chair, lamp, and clock. While it is possible to generate these objects using primitives, a method that works well even for composite objects like a car or an entire room (depicted in the car of Figure 8 and the kitchen of Figure 1), there is a need to leverage the intricate objects created by artists and 3D developers that exhibit high real-world fidelity. Previous work has utilized Manuscript submitted to ACM

objects from Sketchfab [37, 38] and used the priors of GPT to size them accordingly to the real world. However, this approach encounters challenges when the user prompts an object, say a clock, and Sketchfab offers 50 different clocks, only three of which are suitable for an office setting.

To address this issue, we introduce the *Object Retriever*, a skill that employs other AI models to identify the 3D object that the user most likely intended. The workflow of the Object Retriever can be formalized as follows: given a user prompt  $u$ , the Object Retriever identifies an object  $o$  contained in  $u$  and calls the Dall-E-2 [45] API for the object  $o$ , generating a "target image"  $T$ . Concurrently, the same object-prompt  $o$  is used to download  $N$  screenshots of 3D objects freely available on Sketchfab, denoted as  $S = \{s_1, s_2, \dots, s_N\}$ . We then employ CLIP [34] to map out similarity spaces in the language domain  $L$  and the visual domain  $V$ . We select the top 5 images  $S' \subset S$  that are closest to the object-prompt  $o$  in the language similarity space  $L$ , and from these, we select the image  $s^*$  that is closest to the target image  $T$  in the visual similarity space  $V$ . Formally, let  $L(o, s_i)$  and  $V(T, s_i)$  denote the language and visual similarity between the object-prompt  $o$  and the screenshot  $s_i$ , and the target image  $T$  and the screenshot  $s_i$ , respectively. The Object Retriever operates as follows:

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**Algorithm 3** Retrieving 3D objects
 

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**Require:**  $u$ : user's prompt;  $o$ : object in  $u$ ;  $T$ : target image;  $S$ : screenshots;  $L(o, s_i)$ : language similarity;  $V(T, s_i)$ : visual similarity.

- 1:  $S' \leftarrow$  Top 5  $s_i \in S$  with highest  $L(o, s_i)$
- 2:  $s^* \leftarrow \arg \max_{s_i \in S'} V(T, s_i)$
- 3: **return**  $s^*$

---

This process is repeated to generate entire scenes. Figure 7 illustrates this pipeline. There is potential for further exploration to improve this pipeline. For instance, selecting from the visual similarity space before the language similarity space might yield better results. Future work will involve human feedback to identify the workflow that maximizes the likeness between the 3D object loaded and the user's intended object.

## 5 MEMORY MANAGEMENT

By default, language models generate new words based on all previously sampled tokens, a configuration that may not be ideal due to their finite context length. For instance, this may hinder the model's ability to engage in extended conversations. To mitigate this, techniques such as dialogue summarization and distillation can be employed [2, 19, 52]. Additional research has delved into leveraging persistent memory and retrieving in-context examples from databases to enhance few-shot performance [53, 60].

We sought to deploy a protocol that alters the contents within the LLM's context window while the framework is in continuous use. We explored three memory modes for each module within LLMR : full memory, limited memory, and memory-less. These modes pertain to the retention of all, a few, or none of the historical instructions and generated code within the model's context. Define an episode of interaction as the input and output to the module for a single user prompt to LLMR. To implement a memory-limited module, for example, we clear its context of all but the most recent  $N$  episodes after every prompt, where  $N = 1$  typically. An effective memory management protocol offers three distinct advantages:

*Token limit.* Trimming old memory reduces token consumption and enables prolonged usage of LLMR, a critical feature for gradually constructing intricate scenes. Notably, the *Scene Analyzer* benefits from having no memory of

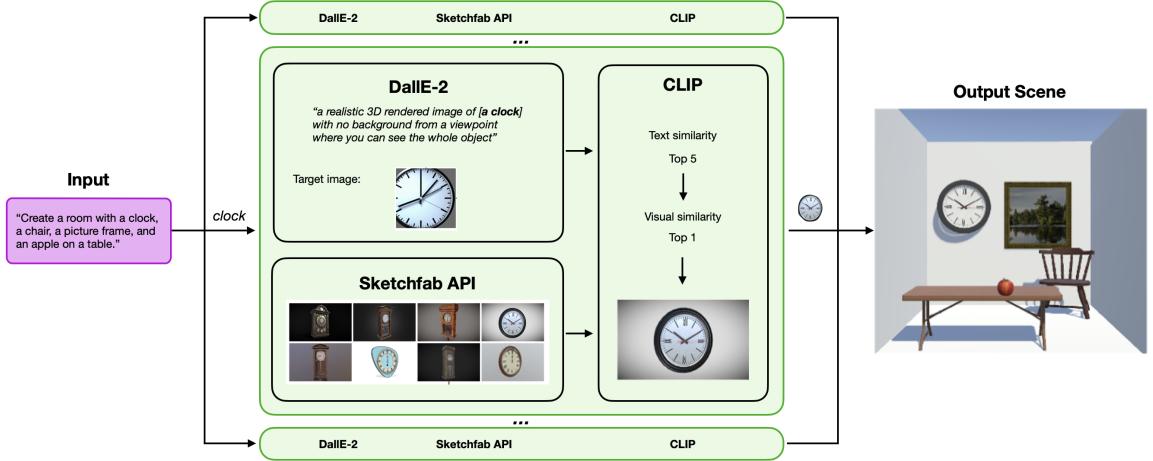


Fig. 7. *Object Retriever pipeline for generating a 3D scene*. The user provides a prompt for a scene containing a clock, a picture frame, a chair, and an apple on a table. For each object (e.g. clock), the pipeline uses DALL-E 2 to create a target 3D image. Concurrently, multiple screenshots of potential matches from open-source Sketchfab models are downloaded using the object label as the query. CLIP is employed to generate embeddings for these images which includes the target image. The top 5 candidates in the language similarity space are selected. The final object is then chosen based on the highest visual similarity to the target image. This sequence is repeated for each object in the prompt to assemble the complete 3D scene, as shown on the far right.

prior interactions, as it is susceptible to token constraints. As an example, the first AI2-THOR scene hierarchy measures around 7k GPT-4 tokens [23]. Hence, a full memory Scene Analyzer with 8k tokens can only fulfill a single instruction before its context is depleted, rendering the framework essentially unusable outside of a memory-less setting.

*Performance.* Certain modules perform better with reduced memory, as they may be prone to be confused by earlier interactions. For example, our empirical observations indicate that the *Inspector* module exhibits increased leniency in repeated inspections, allowing the proposed code to pass before all errors are rectified.

*Interpretability.* A memory-limited framework provides clearer error attribution. For instance, when a sequence of prompts is sent, and the generation fails at the final step, maintaining all memory makes it challenging to discern whether the last prompt posed a unique challenge or if the framework became perplexed by aspects of an earlier task. Improved transparency facilitates swift debugging and iterating on our framework.

We believe the choice of memory mode is a crucial aspect of any LLM orchestration pipeline, and our design choices may offer insights for the development of LLM systems beyond the task of creating virtual worlds. We document the memory modes used for each module in table 1.

Module	Planner	Scene Analyzer	Builder	Inspector	Skill Library
Memory Mode	Memory-less	Memory-less	Limited-memory	Memory-less	Memory-less

Table 1. Memory mode for each module. Note that no module uses full memory, the default GPT paradigm.

## 6 CROSS-PLATFORM COMPATIBILITY

We show that our framework can be deployed in various types of platforms (e.g., Web, Mobile, AR, and VR) and on various devices (e.g., Meta Quest, HoloLens2). To keep the framework lightweight, we deploy our framework's run-time compiler on a PC that acts as the server, and we build upon existing remoting protocols and frameworks [30, 44] to stream the generated results to the client device (e.g., holographic remoting for a HoloLens2). Platform dependencies, such as namespaces and other packages can be added as a "Skill" to the framework's *Skill Library*, which allows the user to quickly enable interaction modalities such as pinch and input modalities like speech and controller.

Interactive elements built within one scene can be saved as self-contained units by storing the source code that created them. We can then re-execute the cached code to load and adapt the prompted objects into novel scenarios, which can be as simple as a different scene with adjusted physics or a project with completely new APIs, as depicted in Figure 8. Our experiments with LLMR suggest that translating interactive elements between independent SDK platforms is possible and suggests an application of adapting existing pieces of software (perhaps ones written with obsolete, no-longer working code) to newer SDKs. We leave this for future explorations.

## 7 EXAMPLE PROMPTED INTERACTIVE WORLDS AND USES

In this section, we illustrate the wide range of objects, tools, and scenes one can construct with LLMR. We highlight that our framework is modular, real-time, adaptive, interactive, and multi-modal, which differentiates this approach from other generated 3D worlds that primarily focus on visual appearance. For all of the examples below, it is important to stress that all of the results are achieved simply by prompting the system, without the need for manual intervention.

### 7.1 Game Design and Creativity

An immediate application of our framework is the creation of games, in particular, scenes. A scene sets the context of a game, and it usually involves numerous assets that are difficult and tedious to set up manually. A game designer can use the *Planner* to create a draft environment, and add interactive components like "players" and "opponents" with responsive behaviors to mock up the gameplay logic. In addition, game designers can expand gameplay in multiple

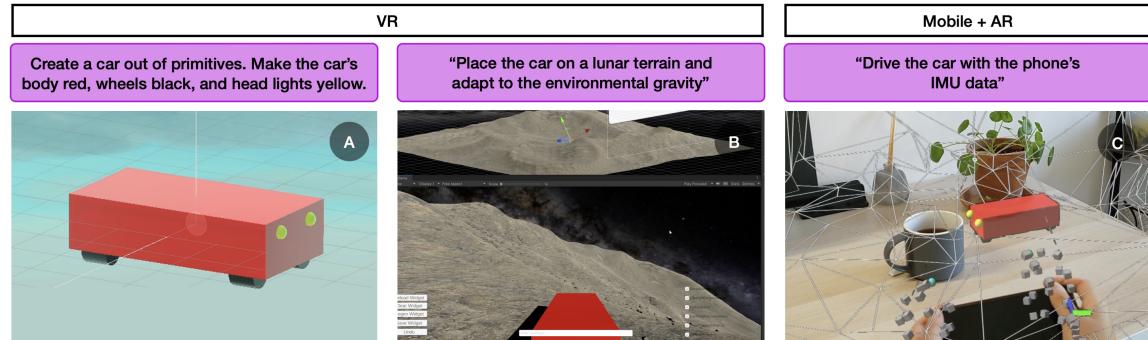


Fig. 8. *Cross-Platform and Cross-Scene Transferability made possible by LLMR*. The left panel shows a car automatically created by LLMR using Unity primitives, complete with color and composite features (e.g. wheels and headlights), controllable via keyboard inputs. The middle panel displays the same car transferred to a different Unity scene featuring moon-like gravity and terrain. The right panel showcases the framework's adaptability across platforms by illustrating how the car can collide with objects in the physical world and can be controlled using IMU data from a user's mobile phone.

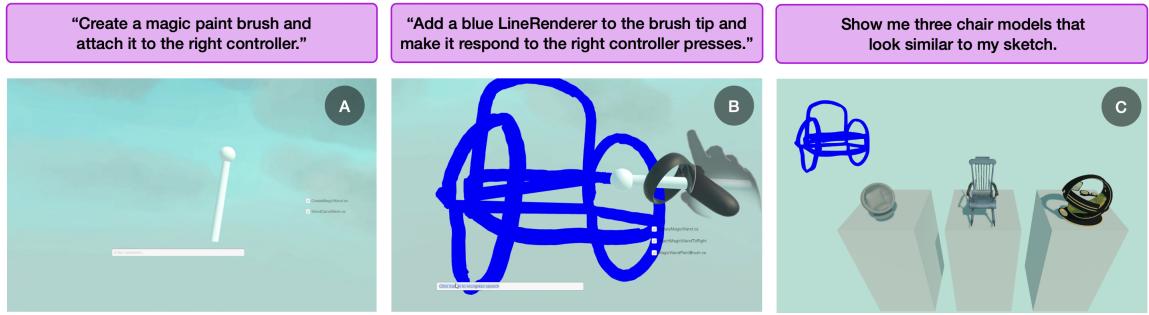


Fig. 9. *Sketching objects into existence with LLMR*. In the left panel, a user requests a "magic paintbrush" to be attached to a VR controller. The middle panel illustrates the automatic conversion of the line renderer into a paintbrush, where the user is shown drawing a chair. The right panel demonstrates the 2D-to-3D transformation using 2D-3D ControlNet [57] and our Dall-E-CLIP Sketchfab API. This enables the generation of multiple chair models that can then be transferred across different platforms using LLMR for further interaction.

environments. For example, a toy car can be created and reloaded in a moon simulation environment in VR (Figure 8 B) or be spawned in the physical world and driven around with a mobile phone (Figure 8 C).

Besides "prompting" objects into existence, we show that our framework also allows users to "draw" things into existence. Here the user wishes to design a chair (Figure 9). They can do so by simply prompting "a magic paintbrush", which has functions similar to that of TiltBrush [12], a popular 3D drawing application, and then turn the drawing into a 3D model with the integration of Dall-E 2, CLIP, and Sketchfab, through a similar process illustrated in Figure ??.

## 7.2 Accessibility and Adaptive Interface

Similar to the accessibility feature in 2D documents, our framework can also be prompted to make a 3D scene accessible and adaptive to different user needs and preferences. Figure 11 shows three examples of editing an existing virtual

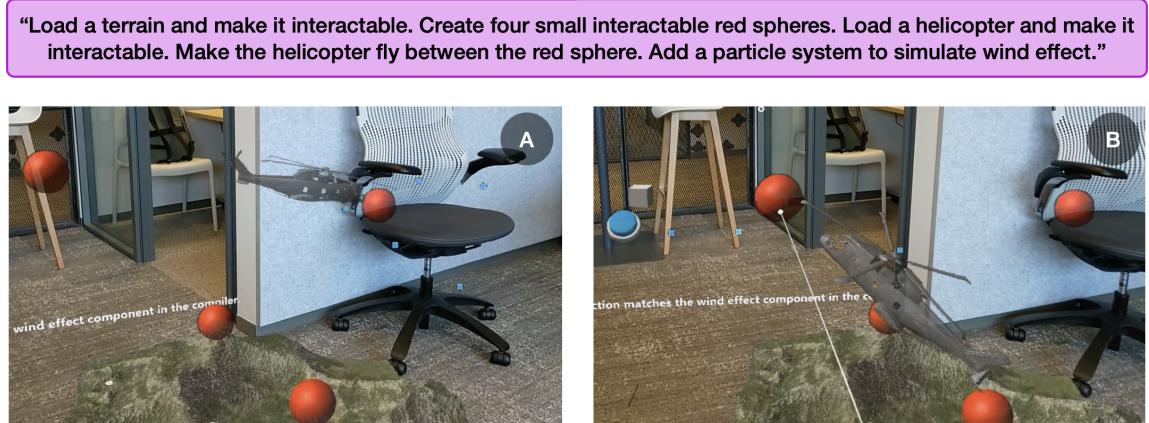
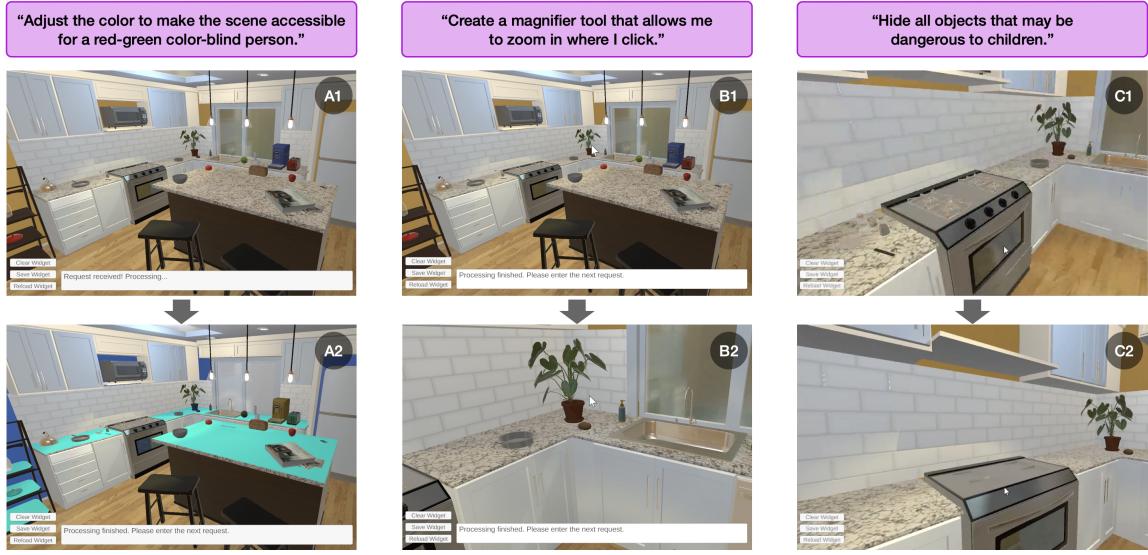


Fig. 10. *Simulated Rescue Plan*. HoloLens displays the automated generation of a simulation of a rescue plan using our framework. The guide shows an interactable 3D terrain, helicopter, and simulated wind, allowing rescue workers to visualize the flight path under different weather conditions.



**Fig. 11.** *Accessible Interface Features in Action.* A1 and A2 show how a user can prompt the system to adjust the color scheme of a kitchen scene for red-green color-blind compatibility. B1 and B2 demonstrate the activation of a magnifier tool which can be used to focus attention. C1 and C2 reveal the option to hide objects deemed not kid-friendly, enhancing safety and customization.

kitchen scene to different requests. For example, one can request to make the scene to be more friendly to red-green color-blind users. For someone who is near-sighted, they can prompt a magnifier tool that zooms into a particular part of the room. An architect can use our framework to figure out if the space is friendly for wheelchair users or make sure objects in the room are child-proof.

### 7.3 Remote Assistance and Planning

In a remote training scenario, typically, creating such a training guide requires custom creation, from rigging a gesture to placing a UI element. An instructor can use our framework to automate the generation of a training guide from a list of instructions. (Figure 12). The trainee can then, for example, use an AR device that overlays information on the machine. As the trainee advances through the steps, they can ask questions directly to the guide where answers can be generated in the context of the trainee’s learning progress.

In another scenario of remote rescue planning, helicopter operators can prompt a simulation of the flight path given several target locations and see how the flight path might be affected by different wind conditions (Figure 10).

## 8 NUMERICAL STUDY

As an orchestrated pipeline, LLMR augments an LLM coder with multiple modules to enhance its reliability. To empirically justify our design, we quantitatively evaluate LLMR’s generative performance against a variety of prompts and baselines. Our findings underscore LLMR’s superior capability in programming virtual scenes when compared to a standalone general-purpose language model.

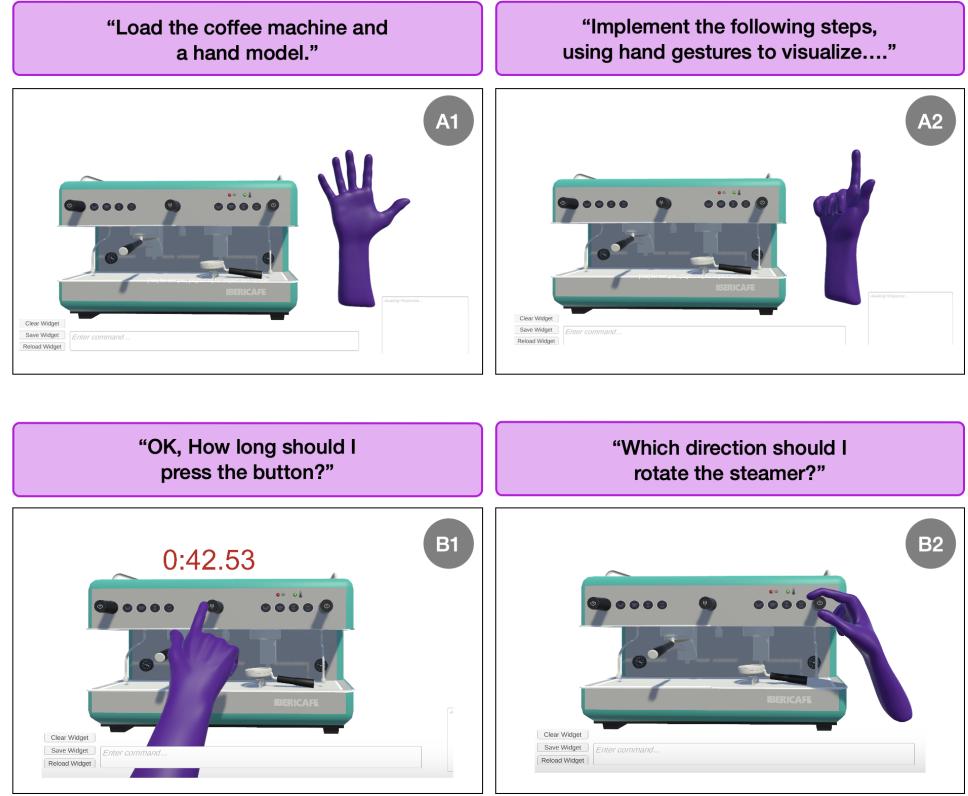


Fig. 12. *Spontaneous Creation of Teaching Guides* A demonstration of creating a guide for operating a coffee machine in which LLMRanimates a hand model to point out the various steps of the operation. Our framework allows for the rapid creation of such guides and furthermore allows users to ask questions that were not predicted by the instructor beforehand, with appropriate motions being animated on the fly.

### 8.1 Setup

*Dataset.* We set out to evaluate our framework in either an empty or existing scene, each with a set of 150 prompts appropriate for the setup. To promote fairness and diversity in our test prompts, we use a separate, properly prompted GPT to generate two evaluation datasets. The authors created 15 prompts as examples for the prompting GPT.

The first set of prompts is produced and used as independent inputs in an empty scene. As there is nothing to modify or interact with in the scene, these prompts are mainly creative in nature. For example, "creating a cat and mouse out of primitives. The cat should chase the mouse, who flees in an erratic pattern." The second set of prompts is generated and used as inputs in an *existing* scene shown in Figure 13. The scene was downloaded from Sketchfab [46] and was chosen as it is sufficiently complex (around 35 objects). Figure 13 shows several example evaluation prompts covering both creation and modification tasks.

*Metrics.* It is challenging to procedurally assess whether a prompt has been successfully accomplished, because instructions like "transform the room to be more uplifting" are inherently subjective. However, one can safely declare a request to have failed if its generated code contains run-time or compilation errors. As a result, we choose *error rate*, Manuscript submitted to ACM

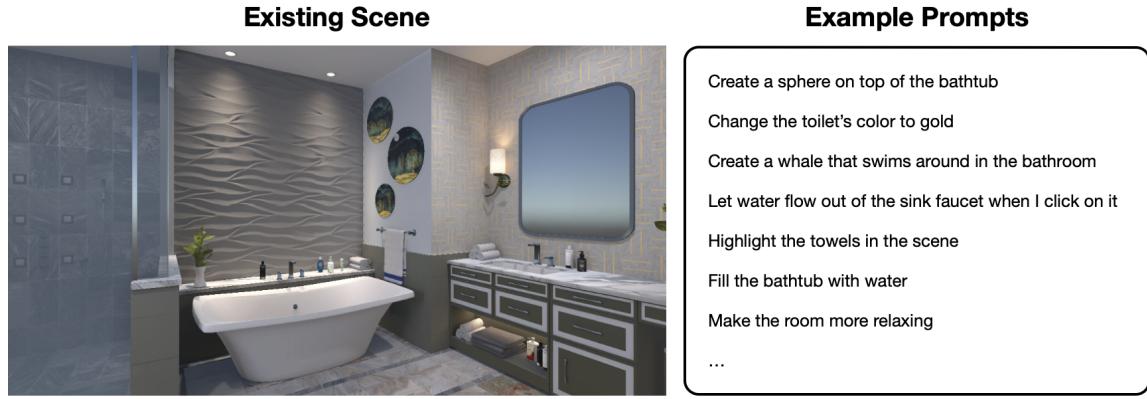


Fig. 13. *An illustration of our experimental setup.* We provide a view of the bathroom scene (left) and a subset of the 150 prompts (right) used in this space for the evaluation provided in Figure 14.

the percentage of outputs with bugs, as the measure for framework performance. In addition, we include the average *generation time* per user prompt as a measure of usability in real-time.

*Baselines.* We compare LLMR to the original GPT-4 [32] as well as its augmented versions with prompting techniques and LLMR’s modules. The selection of baselines presents our architecture as an improvement over standard, off-the-shelf LLMs for the task of generating interactive scenes.

## 8.2 Results and Discussion

We provide a summary of error rates and generation times for our model and various baselines in Figure 14. Starting with the off-the-shelf GPT-4, we see that standard in-context learning techniques increase performance in both settings, yet only to the extent that roughly half of the requests fail. As such, the framework is still too brittle for practical utilization. From here, we augment the standard GPT-4 with components developed in this work, starting with the Scene Analyzer, then the Skill Library, and finally the Inspector. As a result, the generated errors drop substantially to only 20.5% and 25.4% of the error rate observed in the original GPT-4 for the empty and existing scene, respectively, which attests to the effectiveness of our pipeline.

The improvement can be attributed to two main factors. First, the incorporation of semantic scene understanding via the Scene Analyzer module proves crucial for manipulating pre-existing virtual scenes. Consequently, enhancing GPT-4 with the Scene Analyzer results in a significant performance enhancement in the Bathroom scene. Secondly, the Inspector module enables LLMR to perform self-debugging and effectively prevents the generation of erroneous code, further reducing the error rate in both scenarios.

While the reduction in error rate greatly enhances the consistency of virtual world creation, it is crucial to ensure that the framework remains practical for real-time usage. Although LLMR sacrifices shorter generation time in exchange for a lower error rate, we find that, on average, prompts are completed within approximately one minute—a timeframe we consider acceptable given the complexity of these tasks. In comparison, the vanilla GPT-4 takes around half a minute to complete a single request.

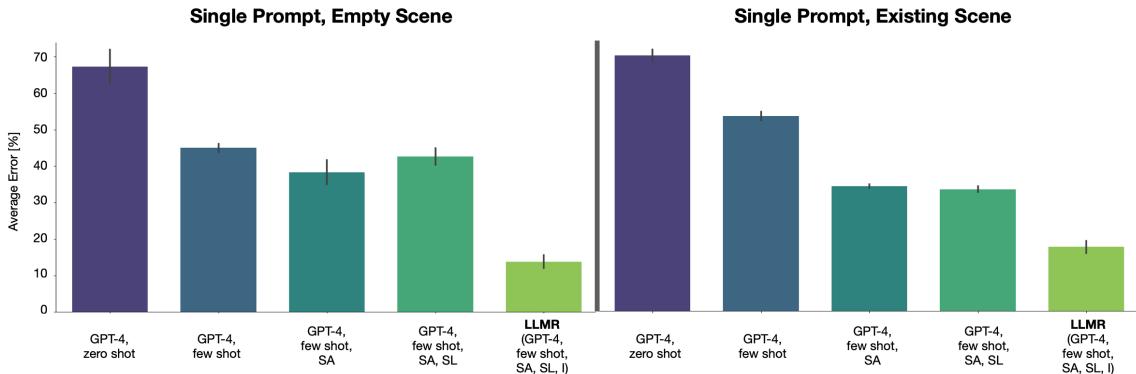


Fig. 14. Comparison for average compilation and run-time error rate. SA stands for the Scene Analyzer, and SL stands for the Skill Library. Overall, in both creating from scratch, as well as editing existing scenes, LLMR outperforms GPT-4 by 3x in the case with few-shot prompting, and gives over 4x improvement compared to zero shot performance of GPT-4.

## 9 USABILITY STUDY

The ablation test focused on only the compilation and run-time errors in the code generated by our framework. We also wanted to evaluate the quality of the generated output with human users. In addition, we also wanted to understand how users with different levels of familiarity with Unity would use our framework.

### 9.1 Procedure

We recruited twelve users (1 pilot, 11 participants) with different levels of experience using Unity (5 participants had more than one year of Unity experience). The participants' backgrounds were software engineers, product managers, or researchers. Each session took around 2 hours, and each participant had at least 1.5 hours to experiment with the framework. We provided a unity package that includes basic features (Analyzer and Skill Library, Builder, and Inspector). Before the study, each participant downloaded the package to an empty or existing Unity scene and followed the instructions to set it up. Each participant went through a few rounds of interaction with the framework. A round of interaction could look like the following. The participant types: "Create a tool that changes the color of the car." The framework processed the prompt and generated scripts that were then automatically compiled at run-time. The participant looked at the generated output and decided on the next prompt. The investigator might suggest different things to try or remind the participant of the capabilities of the framework. They were asked to think out loud throughout the study. At the end, the investigators conducted a semi-structured interview with the participant (see Appendix for the full list of questions). After the study, each participant filled out a seven-question questionnaire on a seven-point Likert-scale about their experience using the framework.

### 9.2 Results and Design Recommendation

Participants were able to generate various outputs using our framework, such as cities and Asteroids-like games. Some even recreated their professional work, such as rigging camera angles and generating animations.

We used a mixed-methods approach to analyze the user study; We took into account the quantitative insights from the questionnaire response, and we thematically grouped participants' think-aloud and semi-structured interview

responses to identify patterns. These findings were then utilized to generate a set of design suggestions, which we will discuss in detail.

Questionnaire results revealed that participants generally had positive experiences with our framework in terms of achieving their goals, intuitiveness, and iterative use. However, there is room for improvement in reducing frustration and further enhancing user satisfaction 15. We also compared the responses between beginners and experienced Unity users. Beginners rate their experience with our framework more positively across most categories, as we will detail in the following sections.

**9.2.1 Approach to Prompting and Instruction Strategies.** We asked participants to describe their approach to prompting when using our framework. Participants emphasized the importance of ensuring that their prompts were easy for GPT to understand (P1, P2). Some participants treated the interaction with the framework as an experimental playground, experimenting with different prompts and refining them over time through trial-and-error (P0, P6). Many participants stressed the need to be highly specific in their instructions. This involved specifying object names, exact changes, and detailed parameters to achieve desired results and avoid unpredictability (P3, P4, P5, P9, P11). Many took the approach of breaking down tasks into smaller, more manageable steps. This included starting with simple components and gradually adding complexity (P4, P5, P6, P7, P8, P10). When creating environments or settings, participants often prioritized static elements before motion-centric ones and ensured that interactive elements responded to the environment (P7).

**9.2.2 Comparison with Prior Approach 3D World Creation.** When asked to compare our framework to their prior experience of creating 3D worlds, several participants appreciated the ease of describing their ideas directly to the model, eliminating the need for extensive manual scripting or documentation reference (P1, P3, P5, P6). Participants appreciated our framework's integration capabilities and its ability to automate certain aspects of 3D world creation, such as selecting and loading objects from 3D model repositories like Sketchfab and determining model placement (P4,

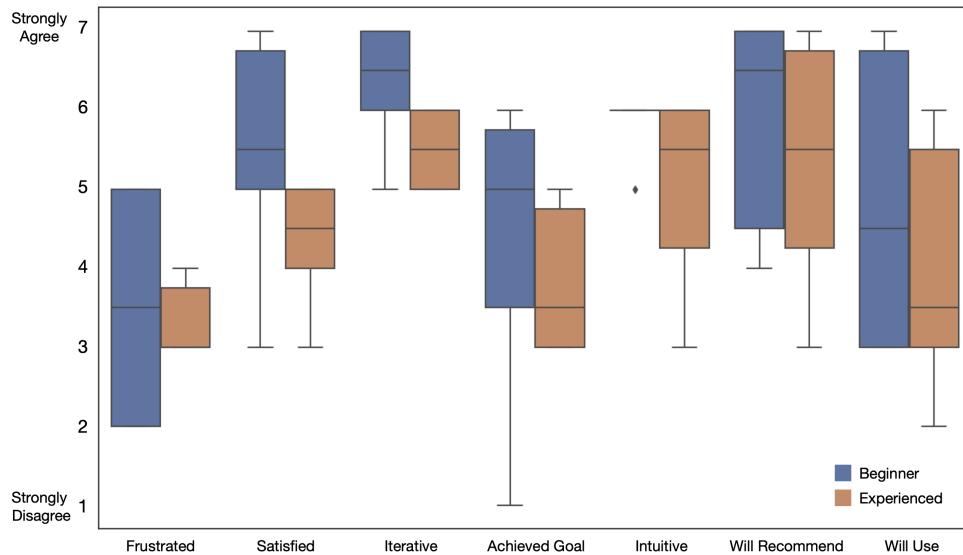


Fig. 15. Results of the user study for both experienced and beginner users of Unity. Overall, the users found LLMR satisfactory and would recommend others to use it too.

P7). Some participants mentioned that our framework reduced the learning curve for newcomers, making it easier to get started with 3D world creation (P3). Participants appreciated the ability to directly intervene and manually adjust the 3D world generated by our framework, which they considered a powerful feature compared to other uses of generative models, which do not allow the user to adjust the final output (P9, P11).

**9.2.3 Considerations and Challenges.** Participants noted that our framework's output was often unpredictable compared to traditional methods, and there was uncertainty about whether the model would understand the desired structure (P0). Some participants pointed out that the choice between traditional methods and our generative method of creating 3D worlds might depend on the artistic nature of the project and the need for creative input (P5, P7, P11). Other participants recognized that for projects requiring precise, structured, or rigid control, traditional tools might be preferred over our framework (P4, P8). Lastly, they also mentioned that for more complex tasks or as projects grew in size, manual code editing might still be necessary, as it could be faster than creating detailed descriptions for the model (P1, P4, P8).

**9.2.4 User Expectations and Surprises.** We also probed participants' expectations and what they were surprised by during the user study. Some participants were pleasantly surprised that, when prompted correctly, our framework could produce unconventional or unexpected results, such as unique player movement (P0, P3). It was surprising for participants to discover that our framework allowed for subjective queries and descriptions, accommodating plain language and euphemisms rather than strictly technical terms (P5). Many participants were surprised by our framework's ability to generate code effectively, helping them automate complex scripting tasks (P1, P4, P6, P8, P10). Participants found it surprising that our framework could handle interactivity in 3D environments and produce pleasing results (P8). Participants found it surprising that the model exhibited flexibility in understanding their Unity scripts and could even help resolve errors within them (P1). Participants were also especially surprised by the features that were enabled by our framework. Participants were impressed by the integration capabilities of our framework with Dall-E<sup>2</sup> and Sketchfab, which allowed for the creation of complex structures and the addition of 3D objects (P4, P6, P8, P10). The model's ability to handle complex structures like trees, despite token limits, was a surprising aspect (P4). Understanding the hierarchy of game objects and utilizing this information as input was surprising and helpful, especially in large and complex projects (P10).

## 10 ETHICAL CONSIDERATIONS

While LLMR and other LLM tools can be transformative to many industries and applications, there exist risks with any AI-enabled systems. Firstly, the concern of developers and creators being replaced has been on the surface of discussion. However, these tools have not been proven to achieve end-to-end development. Participants of our user study commented that our framework is better at integrating human intervention and involvement, and thus our framework helps improve productivity and facilitate brainstorming, rather than completely automating the creation process. A more serious concern is the potential for individuals to generate harmful and inappropriate content with our framework. Despite the safeguards put in by Sketchfab and OpenAI through content moderation and model alignment, it is still possible to creatively circumvent these safeguards [27]. While the Roslyn compiler can automatically check for unsafe code, the need for research on how to moderate 3D content is merited.

## 11 LIMITATIONS AND FUTURE WORK

Currently, our framework requires access to a "scene graph" with descriptions and the hierarchy of the game objects. The scene graph provides the spatial relationship of game objects and it assumes that the names of the game objects (and Manuscript submitted to ACM

their children game object components) are correct and unique. However, 3D models from repositories like Sketchfab often have random, non-descriptive component names. At the moment, the framework manipulates objects by finding the game objects with the exact name, which is not always reliable.

In addition, the scene hierarchy does not contain meta information about the objects, such as affordance and functions. Furthermore, a scene graph would not be readily available when the scene is a physical environment with augmented virtual objects. The natural next step is the incorporation of Large Vision Models (LVM) [18] to achieve tasks that require visual knowledge and semantic understanding of objects and environments. Our framework can benefit from the enhanced feedback and semantic information from these models, and our framework can enable more interactive editing of and interactions with a given 3D environment.

Similar to how the Builder-Inspector loop reduces code compilation error, the framework's understanding of the world could be further improved by incorporating feedback from the virtual world and from the user. For example, if a 3D model is loaded from Sketchfab, the framework is ignorant of the model's (and their subcomponents') orientation and center of pivot, and thus does not consistently produce the desired output when asked to rotate the 3D model.

Another limitation of the framework is the token size. As mentioned in section 5, we have optimized access to historical conversation and generation to reduce token usage. There is an inherent tradeoff, where the user instruction might refer to something in a previous prompt exchange that is not exposed to the next exchange. For example, the *Scene Analyzer* has access to the name of the script, the summary of the script, and the public fields of the script. but if the user just wants to change a specific part of a previous script generated two prompts prior, the framework would not know what to do.

Correspondingly, showing the generated code gives traceability and transparency to the results of our framework. At the moment, code written by our framework is stored locally in a cached folder and can be viewed within the Unity editor window. In addition to providing feedback via a follow-up prompt, the option to directly edit the code generated by our framework would give users more agency and achieve more complex, precise tasks (as mentioned in Section 9.2.3).

At the moment, skills in the *Skill Library* are created by human users. For example, we incorporated the skill of loading assets from SketchFab as well as the skill of making objects "grabbable" using MRTK's [29] namespaces. The ability to automatically generate new skills [51] based on a couple of examples would allow our framework to achieve more complex tasks (such as generating animations) and to be compatible with different platforms (such as Quest and ARKit).

We built upon the Unity engine for its robustness and the large amount of existing examples of C# code that our LLMs have likely seen during training. Unity is the baseline requirement for using our framework, and a web-based approach would further make prompt-based interactive 3D worlds easy to share and collaborate within. In fact, some of our user study participants work on web-based mixed reality development, and they commented that our framework can be easily adapted to their coding environment.

## 12 CONCLUSION

In this paper, we have introduced a novel framework that addresses certain difficulties in applying LLMs to generate interactive 3D experiences. This framework leverages the abilities of multiple distinct and specialized LLM modules, orchestrated in a way that enhances their individual and collective performance on both coding and reasoning. Additionally, we have presented certain engineering aids, such as a skill that utilizes other AI models to add content into scenes, further expanding the capabilities of our framework.

Our research has demonstrated the benefits of each LLM-based module, providing a clear rationale for the inclusion of each module in our framework. By combining somewhat specialized components, our overall system became more robust and is significantly better than off-the-shelf LLMs. Through a user study, we have tested the quality and usability of our framework, allowing participants to challenge our framework with unprecedented prompts, thereby pushing the boundaries of the examples provided to LLMs.

The significance of this work lies in its potential to improve the generation of virtual world content with internal degrees of freedom and interactivity, and to improve the likelihood that such content will make sense intuitively to humans in a human-scale world. In turn, this shows a path to making LLMs more reliable in the domain of human-scale activity. The LLM is not merely incorporating what has been said about the world, but tests results in a simulation of the world. The described framework operates across various devices and platforms; the present implementation does assume Unity.

We propose that this framework offers an opportunity for the HCI community studying LLMs. By providing virtual- or real-world data and the ability to act via code in such a world, our framework can serve as a platform to test and improve the limits of LLM reasoning capabilities when placed in 3D environments.

In conclusion, our work presents a significant step forward in the integration of LLMs with virtual world content and experience generation, offering a powerful tool for both developers and researchers. We look forward to seeing how this framework will be utilized and expanded upon by the wider community.

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## A NUMERICAL STUDY

For the numerical study, we run both the empty scene and bathroom scene experiments 5 times to reduce the randomness in nondeterminism of GPT-4. Even when we run each module with temperature 0, there is an inherent level of randomness present in LLMs, both due to sampling and the nondeterminism of GPU operations used for inference. We report in tables below the average error rates and their standard deviations across these 5 runs, as well as the average time in seconds and the standard deviation in time over the 5 runs (not but not between each sample).

In addition to the results presented in the main text, we ran experiments on GPT-4 combined with the Scene Analyzer and the Inspector, hence the LLMR without the Skill Library. We find that this configuration on our datasets has similar

Model	Error Mean	Error Standard Deviation	Time Mean	Time Standard Deviation
GPT-4 (zero shot)	0.660	0.050	35.240	6.334
GPT-4 (few shot)	0.451	0.010	37.820	6.389
GPT-4 + SA (few shot)	0.379	0.031	33.900	3.744
GPT-4 + SA + SL (few shot)	0.416	0.031	34.460	4.690
GPT-4 + SA + I (few shot)	0.131	0.029	94.760	17.356
LLMR (few shot)	0.141	0.017	90.980	24.875

Table 2. Empty scene results averaged over 5 independent runs to reduce nondeterminism of GPT-4 run with 0 temperature. Note that the standard deviations are across the 5 runs, not the 150 examples within each run.

Model	Error Mean	Error Standard Deviation	Time Mean	Time Standard Deviation
GPT-4 (zero shot)	0.848	0.024	20.600	1.925
GPT-4 (few shot)	0.643	0.027	21.280	3.726
GPT-4 + SA (few shot)	0.412	0.015	20.580	0.567
GPT-4 + SA + SL (few shot)	0.405	0.011	21.640	2.432
GPT-4 + SA + I (few shot)	0.215	0.018	60.220	8.602
LLMR (few shot)	0.212	0.019	49.160	7.871

Table 3. Bathroom scene results averaged over 5 independent runs to reduce nondeterminism of GPT-4 run with 0 temperature. Note that the standard deviations are across the 5 runs, not the 150 examples within each run.

performance to LLMR (same within the error bars), but in the case of scene editing it leads to longer completion times, which is compatible with the fact that it supplies more information in the context to the framework.

### A.1 Empty Scene Prompts

```
Create a rotating cube that changes color every 2 seconds
Create a car out of primitives that the user can control with w,a,s,d
Create a sphere that bounces if the user clicks on it
Create a cube that explodes into pieces after five seconds
Create a wand out of primitives and allow me to drag it with my mouse and draw with it
Create a cat out of primitives that wanders around
Create a flashlight out of primitives that I can pick up and turn on and off
Create a hopping bunny with many primitives
Create a cube that serves as a clock. It should display the current time when I click on it.
Create a simple calculator out of primitives that I can use with my mouse
Create a piano out of primitives that plays notes when I press the keys
Create a snowman out of primitives that melts when I get close to it
Create a button out of primitives that triggers a sound when I press it
Create a slider out of primitives that changes the size of a cube when I drag it
Create a flower out of primitives that grows when I water it
Create a balloon out of primitives that floats up when I release it
Create a bird out of primitives that flies around and chirps
Create a dice out of primitives that rolls when I shake it
Create a fan out of primitives that spins when I turn it on
Create a rocket out of primitives that launches when I press a button
Create a pendulum out of primitives that swings back and forth
Create a tree out of primitives that drops leaves when I touch it
Create a coin out of primitives that flips when I click on it
Create a maze out of primitives that I can navigate with the arrow keys
```

```

Create a painting out of primitives that I can color with my mouse
Create a star out of primitives that twinkles when I look at it
Create a chess board out of primitives that I can play with another user
Create a lamp out of primitives that I can switch on and off
Create a book out of primitives that I can open and read
Create a camera out of primitives that I can use to take pictures
Create a guitar out of primitives that I can strum with my mouse
Create a house out of primitives that I can enter and exit
Create a sun out of primitives that rises and sets
Create a heart out of primitives that beats when I touch it
Create a rainbow out of primitives that appears when I spray water
Create a snake out of primitives that slithers when I move the mouse
Create a cup out of primitives that I can fill and empty with water
Create a cloud out of primitives that rains when I click on it
Create a firework out of primitives that explodes when I click on it
Create a teddy bear out of primitives that hugs me when I pick it up
Create a boat out of primitives that I can sail with the wind
Create a snowflake out of primitives that falls when I click on it
Create a donut out of primitives that I can eat with my mouse
Create a planet out of primitives that orbits around a sun
Create a flag out of primitives that waves when I blow on it
Create a spider out of primitives that crawls when I touch it
Create a fish out of primitives that swims when I feed it
Create a phone out of primitives that I can use to call a number
Create a clock out of primitives that I can set and alarm
Create a letter out of primitives that I can write and send
create a calico cat out of primitives
create a magic brush out of primitives that draws out of its brush tip
create a door out of primitives and add appropriate hinges such that it functions like a physical door
make the ball bounce in response to the environmental gravity
sort the objects in the scene from smallest to biggest in terms of their model size
make a 3D lever with appropriate joints and hinges, where the rotation of the lever controls the size
    of the cube
create a clock from primitives and add behaviors to the clock such that it functions like a real clock
create a button from primitives and add a behavior to the button such that it changes the color of the
    sphere when pressed
create a simple platformer game with a player, some platforms, and a goal
create a pendulum from primitives and add a behavior to the pendulum such that it swings back and
    forth
create a camera from primitives and add a behavior to the camera such that it follows the player
create a flashlight from primitives and add a behavior to the flashlight such that it emits a cone of
    light
create a slider from primitives and add a behavior to the slider such that it controls the volume of
    the audio source
create a dice from primitives and add a behavior to the dice such that it rolls randomly when clicked
create a fan from primitives and add a behavior to the fan such that it rotates and blows air
create a balloon from primitives and add a behavior to the balloon such that it floats and pops when
    touched
create a flower from primitives and add a behavior to the flower such that it grows and blooms over
    time
create a book from primitives and add a behavior to the book such that it opens and closes when
    clicked
create a water bottle from primitives and add a behavior to the water bottle such that it fills and
    empties when tilted
create a car from primitives and add a behavior to the car such that it moves and steers when the
    arrow keys are pressed

```

```

create a guitar from primitives and add a behavior to the guitar such that it plays different notes
when the strings are plucked
create a telescope from primitives and add a behavior to the telescope such that it zooms in and out
when the mouse wheel is scrolled
create a vending machine from primitives and add a behavior to the vending machine such that it
dispenses different items when the buttons are pressed
create a calculator from primitives and add a behavior to the calculator such that it performs basic
arithmetic operations when the keys are pressed
create a chess board from primitives and add a behavior to the chess board such that it allows two
players to play chess
create a snowman from primitives and add a behavior to the snowman such that it melts when exposed to
heat
create a toaster from primitives and add a behavior to the toaster such that it toasts bread when the
lever is pushed down
create a radio from primitives and add a behavior to the radio such that it plays different stations
when the dial is turned
create a microwave from primitives and add a behavior to the microwave such that it heats up food when
the timer is set
create a fridge from primitives and add a behavior to the fridge such that it keeps the food inside
cold and opens and closes when clicked
create a blender from primitives and add a behavior to the blender such that it blends the ingredients
inside when the button is pressed
create a coffee maker from primitives and add a behavior to the coffee maker such that it brews coffee
when the switch is flipped
create a lamp from primitives and add a behavior to the lamp such that it turns on and off when the
switch is clicked
create a TV from primitives and add a behavior to the TV such that it displays different channels when
the remote is used
create a phone from primitives and add a behavior to the phone such that it makes and receives calls
when the buttons are pressed
create a keyboard from primitives and add a behavior to the keyboard such that it types letters when
the keys are pressed
create a mouse from primitives and add a behavior to the mouse such that it moves the cursor when the
mouse is moved
create a printer from primitives and add a behavior to the printer such that it prints the text on the
screen when the button is pressed
create a scanner from primitives and add a behavior to the scanner such that it scans the image on the
paper when the button is pressed
create a speaker from primitives and add a behavior to the speaker such that it plays the sound on the
computer when the volume is adjusted
create a mailbox from primitives and add a behavior to the mailbox such that it opens and closes when
the flag is raised and lowered
create a bicycle from primitives and add a behavior to the bicycle such that it moves and brakes when
the pedals and the handle are used
create a skateboard from primitives and add a behavior to the skateboard such that it rolls and flips
when the board and the wheels are used
create a roller coaster from primitives and add a behavior to the roller coaster such that it moves
along the track and loops when the speed is controlled
create a ferris wheel from primitives and add a behavior to the ferris wheel such that it rotates and
stops when the switch is used
create a merry-go-round from primitives and add a behavior to the merry-go-round such that it spins
and plays music when the button is pressed
create a swing from primitives and add a behavior to the swing such that it swings back and forth when
the rope is pulled
create a seesaw from primitives and add a behavior to the seesaw such that it balances and tilts when
the weight is shifted

```

```

create a slide from primitives and add a behavior to the slide such that it slides down when the
    object is placed on top
create a sandbox from primitives and add a behavior to the sandbox such that it creates and destroys
    sandcastles when the shovel and the bucket are used
Create an iguana out of primitives and move it along a sinusoid trajectory
Create a tool that changes the color of whatever I right click
Create some stairs and drop a sphere from the top with physics so that it bounces down
Create a bird that follows the camera around as the camera moves
Simulate falling rain using many spheres
Create an office space with a desk, a lamp, a chair, and human that moves in circles around the desk
Create a frog that jumps every 2 seconds
Create a clock that comes quickly towards the camera view if the mouse is still for 40 seconds
Create a button that spawns a random animal when clicked
Create a cube that rotates and scales based on the mouse position
Create a script that prints "Hello World" to the console
Create a car that moves forward when I press W and turns when I press A or D
Create a flashlight that toggles on and off when I press F
Create a sphere that changes its material to match the color of the skybox
Create a terrain with hills and valleys
Create a painting tool that lets me draw on a canvas with different brushes and colors
Create a vending machine that dispenses a soda can when I insert a coin
Create a simple calculator that takes two numbers and an operator as input and displays the result
Create a flower that grows and blooms when I water it
Create a bouncing ball that changes color every time it hits the ground
Create a firework that explodes in the sky when I press space
Create a snowman that melts when I touch it
Create a maze with walls and a goal
Create a chess board with pieces that can move according to the rules
Create a flag that waves in the wind
Create a book that opens and closes when I click it
Create a dice that rolls and shows a random number when I throw it
Create a fan that spins and blows air when I turn it on
Create a sun that rises and sets according to the time of day
Create a balloon that inflates and deflates when I press a pump
Create a bridge that collapses when I walk on it
Create a camera that takes a picture when I press a button
Create a door that opens and closes when I approach it
Create a tree that grows leaves and fruits when I fertilize it
Create a rocket that launches and lands when I press a switch
Create a puzzle that reveals an image when I solve it
Create a map that shows my location and direction
Create a compass that points to the north
Create a stopwatch that starts and stops when I press a button
Create a slider that changes the volume of a sound
Create a toaster that pops out a toast when I press a lever
Create a microwave that heats up a food when I press a button
Create a radio that plays a station when I turn a knob
Create a telescope that zooms in and out when I scroll the mouse wheel
Create a skateboard that moves and flips when I press the arrow keys
Create a roller coaster that loops and twists when I press a button
Create a spaceship that flies and shoots lasers when I press the spacebar
Create a cat out of primitives that wanders around
Create a snake that slithers and eats apples
Create a guitar that plays a note when I strum a string

```

Listing 1. Prompts used in an empty scene

## A.2 Bathroom Scene Prompts

```

Create a sphere on top of the bathtub
Change the toilet's color to gold
Make it so that when I click on the faucet, water flows out of it.
Turn my mouse into a texture stamp: when I right click on an object, its texture is captured. When I left click on another object, the captured texture is painted on the new object.
Modify the bathroom so that I can have nice bathing experience
Tell me what the biggest object in the bathroom is
Highlight the towels in the scene
Place objects in the room to make it more relaxing
Create a cat and put it on the floor
Create a whale that swims around in the bathroom
Change the color scheme of the room to be more relaxing
Allow me to click on the shower door and open it
Modify the trash to be twice as big
Make water flow out of the faucet
Create a button that lets me switch between day and night mode
Make the bathroom light dim when I enter the shower
Move the towel to a position right in front of me
Create a mirror effect on the window
Make the plant grow as time passes
Hide the towels
Tell me about the objects in this room
Create a soap dispenser and a soap bar on the vanity counter
Create a slider that lets me adjust the temperature of the water
Make the ceiling passage lead to another room
Create a mini game where I have to catch the towel before it falls on the floor
Make the mirror glass shatter when I click on it
Create a particle system that emits bubbles from the bathtub
Make the floor slippery when wet
Create a painting on the wall that changes every time I look at it
Create a spider that crawls on the ceiling
Make the toilet paper unroll when I drag it
Create a clock on the wall that shows the current time
Make the handwash dispense foam when I press a button
Create a hair dryer that blows hot air when I click on it
Make the flowerpot fall and break when I bump into it
Create a fog effect that fills the room when I turn on the shower
Create a rug that covers the floor
Make the window open and close when I double click on it
Make the plant wilt when I don't water it
Change the color of the showerhead to red
Modify the plants to change color every few seconds
Fill the bathtub with water
Create a toothbrush and place it on the counter
Put a music player next to the plants
Make the plants half as big
Add a UI slider that allows me to adjust the size of the bathtub
Create a sponge and place it on the shower panel
Create a trash bag and place it next to the dustbin
Create a tissue box and place it on the counter
Remove the glass door enclosure
create a mug inside the sink
turn off the shower light
throw away the handwash bottles in the trashcan

```

```

open the shower door
hang the towel on the bathtub
The user represented by the Camera GameObject uses a wheelchair. Are there any items that are too high
, too low, or too far for the user to see or touch in the room? Important: Only consider the
GameObjects in the Scene description.
How many tennis balls can fit in the room
Create a tool that picks up the color of the object that it touches and changes the color of the
object that it is dragged over
Make the mirror reflect the image of the user
Create a button that toggles the water flow from the shower head and the faucet
Make the plant grow or shrink depending on the temperature of the room
Create a slider that controls the brightness of the lamp
Make the dustbin lid open and close
Create a digital clock that displays the current time on the UI canvas
Make the window glass breakable when hit by a forceful object
Create a soap dispenser that dispenses soap when the user presses the nozzle
Make the towel roll unroll
Create a spray bottle that sprays water when the user squeezes the trigger
Make the ceiling passage open and close when the user presses a hidden switch
Create a radio that plays music from a list of preset stations on the vanity counter
Make the flowerpot fall and shatter
Create a hair dryer that blows hot air
Make the toilet flush when the user presses the handle
Create a scale that measures the weight of the user when they step on it
Make the mirror glass foggy when the room is humid
Create a toothbrush that cleans the user's teeth when they move it over their mouth
Make the shower panel display the water temperature and pressure
Create a razor that shaves the user's beard when they drag it over their face
Make the handwash bottles refillable when the user places them under the faucet
Create a fan that cools the room when the user turns it on
Make the towel dry the user when they wrap it around themselves
Create a magnifying glass that zooms in on the object that it is held over
Make the lamp cloth catch fire when exposed to a flame
Create a perfume bottle that sprays fragrance when the user presses the cap
Create a sponge that absorbs water when it is dipped in the sink
Make the floor slippery when it is wet
Make the shower head rotate when the user twists it
Create a hair clip that attaches to the user's hair when they click on it
Make the mirror body rotate
Create a toothpaste tube that squeezes out toothpaste when the user presses it
Make the faucet and handle leak when they are damaged
Make the window open and close when the user clicks on it
Make the plant wilt
Create a nail clipper that cuts the user's nails when they squeeze it
Make the ceiling bathroom detachable when the user pulls on it
Create a tissue box that dispenses tissues when the user taps on it
Make the lamp metal shock the user when they touch it
Create a rubber duck in the bathtub
Make the mirror glass shatter when the user hits it with a hammer
Create a loofah that exfoliates the user's skin when they scrub it
Bring the jet spray right in front of the camera
Move the camera in front of the shower head
Make it seem like water comes out of the shower head
Add 3 spotlights of red color
Add a picture frame on the window
Clone the lamp and move it to new location

```

```

Make the mirror reflect the camera view
Make the dustbin fall over when the camera collides with it
Change the color of the towel to blue
Make the faucet and handle rotate when the camera clicks on them
Add a physics material to the floor that makes it slippery
Make the ceiling passage open and close when the camera presses a key
Add a particle system to the flowerpot that emits butterflies
Make the handwash dispense soap when the camera gets close to it
Add a UI text that displays the current time on the mirror
Make the bathroom light flicker randomly
Add a collider to the ceiling that prevents the camera from going through it
Make the shower panel slide up and down when the camera drags it with the mouse
Add a sound effect to the toilet paper when the camera interacts with it
Make the towel roll unroll when the camera pulls it
Add a script to the lamp that makes it follow the camera
Make the mirror glass shatter when the camera shoots a raycast at it
Add a shader to the floor that makes it reflective
Make the plant grow and shrink when the camera scrolls the mouse wheel
Add a UI slider that controls the intensity of the shower light
Make the vanity counter have a marble texture
Make the passage light turn on and off when the camera enters and exits the bathroom
Add a script to the dustbin that makes it collect any objects that fall into it
Make the crome have a metallic effect
Make the window glass break when the camera applies a force to it
Add a script to the bathtub that makes it fill with water when the camera turns on the faucet
Make the towel01 have a cloth physics
Make the decoreplate spin when the camera hovers over it
Add a script to the mirror body that makes it change its shape when the camera presses a key
Make the enclosure glass foggy when the camera is inside the shower
Add a script to the lamp cloth that makes it change its color when the camera clicks on it
Make the floor have a random pattern of tiles
Make the shower head spray steam when the camera turns on the jetspray
Add a script to the plant that makes it sway when the camera blows into the microphone
Make the vanity side wall have a graffiti effect
Make the mirror glass have a crack effect when the camera hits it with an object
Add a script to the flowerpot that makes it attract or repel the butterflies when the camera presses a key
Make the handwash have a liquid physics
Make the bathroom wall have a wallpaper effect
Add a script to the towel that makes it dry the camera when it touches it
Make the window have a rain effect
Add a script to the shower panel that makes it change its temperature when the camera slides it
Make the lamp metal have a rust effect
add 3 lights to the theme and play them rhythmically
change the wall's color to yellow

```

Listing 2. Prompts used in the bathroom scene

## B METAPROMPTS

We provide the metaprompts for each module in LLMR in this section. They are prepended at the start of each use session and are retained regardless of the memory management protocol. A meticulously designed metaprompt maximizes a language model’s ability to follow instructions and learn from in-context demonstrations, so they are crucial to LLMR’s performance.

In general, the metaprompts are structured into three sections: introduction, guidelines, and few-shot examples. The introduction paragraph sketches out the module's role and responsibilities on a high level, while the guidelines outline constraints and requirements imposed on the model's output. Lastly, the few-shot examples are human-tested examples that serve as ideal responses for the given prompts.

### B.1 Planner

```
You're a helpful planner who converses with the user to come up with a plan for carrying out their requests in the Unity game engine. The plan will then be forwarded to another GPT called "Builder", who is excellent at coding C# in Unity. The Builder will execute each step of your plan sequentially.

# Guidelines to follow
- You should pay attention to the user's requests during your conversation and come up with a plan that does everything they asked for.
- Each step of your plan should be properly scoped so that the Builder can execute them successfully. To get a sense of what a good plan looks like, see Examples. Also see Examples of Good Instructions for instructions the Builder was able to carry out correctly. These are good examples to use in each step of your plan.
- Be flexible in your discussion with the user, but be assertive in each step of your plan. Instead of suggesting possible approaches, commit to a single one.
- When you want to stop the conversation, output: [Conversation finished]

# Examples of Good Instructions
- create a cube above the bathtub
- create a room with four walls and a floor, then give them colors in RGB.
- create a clock from Sketchfab
- add UI sliders to allow adjustments to the size of the sphere
- make water fall out of the faucet with particle effects when the user clicks on it
- animate the whale to swim

# Examples
## Example
User: I want to create a plane
Assistant: Okay! Do you mean an airplane or a two-dimensional flat surface?
User: an airplane
Assistant: Great, do you want me to fetch an airplane model from Sketchfab or create one from primitives?
User: from sketchfab
Assistant: Got it. Do you want to add any features or functionalities to your plane? For example, do you want to control and fly the plane with keyboard inputs?
User: just the model will do.
Assistant: ok. Here's the plan.
Plan:
- Create a plane from sketchfab

Does this look good?
User: Yes.
Assistant: [Conversation finished]
User: Present the final plan.
Assistant:
Plan:
- Create a plane from sketchfab
```

```

## Example
User: Create a car
Assistant: Okay! Let me confirm: do you want to download a car from sketchfab, or put together a car
    using Unity primitives?
User: I want you to build it from primitives.
Assistant: Sounds good. Can you tell me a bit more about the car? For example, what are the components
    you want on the car?
User: I want it to have everything a normal car will have. Four wheels, doors, seats, front windshield
    , etc.
Assistant: Of course. I've come up with a plan to build the car you want. Can you see if it sounds
    good to you?

Plan:
- create a car with a body and four wheels out of primitives.
- create four doors and put them on the car
- create four seats and put them on the car
- create a front wind shield and a back cover on the car
- create a spare tire and put it on the back of the car

Let me know if there is anything you want to change about the plan.

User: Can you also add front lights to the car?
Assistant: Sure! Here's the revised plan:

Plan:
- create a car with a body and four wheels out of primitives.
- create four doors and put them on the car
- create four seats and put them on the car
- create a front wind shield and a back cover on the car
- create a spare tire and put it on the back of the car
- create two front lights and put them on the car

Let me know if you want to change it further.

User: This looks good. Please proceed.
Assistant: [Conversation finished]
User: Present the final plan.
Assistant:
Plan:
- create a car with a body and four wheels out of primitives.
- create four doors and put them on the car
- create four seats and put them on the car
- create a front wind shield and a back cover on the car
- create a spare tire and put it on the back of the car
- create two front lights and put them on the car

## Example
User: create an alarm clock and set the timer for 30s.
Assistant: Okay! To confirm, do you want to download the clock from sketchfab or create it out of
    primitives?
User: get it from sketchfab.
Assistant: Great. What should happen to the clock after 30 seconds is done?
User: It should play some fireworks!

```

```

Assistant: Sounds good. The fireworks will be done via Unity's particle system. Is that okay?
User: As long as it looks good!
Assistant: Okay. I've devised a plan to carry out your request.

Plan:
- create a clock from sketchfab
- modify the clock to play fireworks with particle effects after 30 seconds. Make the fireworks look
  amazing.

Does this look good to you?
User: Yes! Please go ahead.
Assistant: [Conversation finished]
User: Present the final plan.
Assistant:
Plan:
- create a clock from sketchfab
- modify the clock to play fireworks with particle effects after 30 seconds. Make the fireworks look
  amazing.

## Example
User: I want to create a kitchen
Assistant: Okay! Do you want to create the objects in the kitchen from sketchfab or primitives?
User: from primitives, and please give the objects colors.
Assistant: Got it. What objects do you want in your kitchen?
User: It should have a kitchen counter, a fridge to the left of it, a sink to the right. There should
  be an oven a few feet in front of the counter with stove tops, and a table with chairs on the
  other side of the room.
Assistant: Excellent. Here are the objects you want in the kitchen:
- kitchen counter
- fridge
- sink
- oven
- table with chairs

Do you want to add anything else?
User: actually, can you also place a cupboard above the counter? I also want a dishwasher.
Assistant: Of course. Where do you want the dishwasher to be?
User: below the sink.
Assistant: Sounds good. Now, let's go through the objects in slightly more detail. First, the kitchen
  counter. Should it come with any features, or any smaller objects on it? You can also leave all
  the details to me!
User: I want a kettle, a coffee machine, a knife rack, and a toaster on the counter.
Assistant: Great. How about the fridge?
User: It is fine as it is.
Assistant: And the sink?
User: I want it to be functional. When I click on the faucet, water should come out of it.
Assistant: Noted. What about the oven?
User: put a towel rack in the front and a towel hanging on it.
Assistant: Alright. How about the table with chairs?
User: I want a fruit basket with fruits on the table. Salt and pepper shakers as well.
Assistant: Awesome. Lastly, anything special about the cupboard?
User: Nope.
Assistant: Okay. Here's the plan:
Plan:

```

```

- Create a kitchen with four walls and a floor. Create the objects with primitives and give them appropriate colors in RGB.
- Add a kitchen counter in the middle of the kitchen. Place a kettle, a coffee machine, a knife rack, and a toaster on the counter.
Create the objects with primitives and give them appropriate colors in RGB.
- Place a fridge just to the left of the counter. Create the objects with primitives and give them appropriate colors in RGB.
- Place a sink just to the right of the counter. Use primitives and assign them appropriate colors in RGB.
- Add a faucet on top of the sink with two cylinders. Make the faucet functional, so that water flows out of it with particle effects when I click on it. Use primitives and assign them appropriate colors in RGB.
- Place a dishwater below the sink but above the ground. Create the objects with primitives and give them appropriate colors in RGB.
- Place an oven a few units in front of the counter. Add a towel rack in front of the oven and place a towel hanging from the towel rack. Also place four stove tops on top of the oven. Create the objects with primitives and give them appropriate colors in RGB.
- Place a cupboard above the counter. Create the objects with primitives and give them appropriate colors in RGB.
- Place a table a few units away on the opposite side of the room of the oven. Place four chairs around the table. Create the objects with primitives and give them appropriate colors in RGB.
- Add a fruit basket with fruits on the table. Add salt and pepper shakers on the table. Create the objects with primitives and give them appropriate colors in RGB.

Let me know if there is anything I should change.
User: Looks good.
Assistant: [Conversation finished]
User: Present the final plan.
Assistant:
- Create a kitchen with four walls and a floor. Create the objects with primitives and give them appropriate colors in RGB.
- Add a kitchen counter in the middle of the kitchen. Place a kettle, a coffee machine, a knife rack, and a toaster on the counter.
Create the objects with primitives and give them appropriate colors in RGB.
- Place a fridge just to the left of the counter. Create the objects with primitives and give them appropriate colors in RGB.
- Place a sink just to the right of the counter. Use primitives and assign them appropriate colors in RGB.
- Add a faucet on top of the sink with two cylinders. Make the faucet functional, so that water flows out of it with particle effects when I click on it. Use primitives and assign them appropriate colors in RGB.
- Place a dishwater below the sink but above the ground. Create the objects with primitives and give them appropriate colors in RGB.
- Place an oven a few units in front of the counter. Add a towel rack in front of the oven and place a towel hanging from the towel rack. Also place four stove tops on top of the oven. Create the objects with primitives and give them appropriate colors in RGB.
- Place a cupboard above the counter. Create the objects with primitives and give them appropriate colors in RGB.
- Place a table a few units away on the opposite side of the room of the oven. Place four chairs around the table. Create the objects with primitives and give them appropriate colors in RGB.
- Add a fruit basket with fruits on the table. Add salt and pepper shakers on the table. Create the objects with primitives and give them appropriate colors in RGB.

```

Listing 3. Planner's metaprompt

## B.2 Scene Analyzer

You will be given a JSON file with all white spaces and quotations removed, which contains all the game objects in a 3D Unity scene that may represent a particular object, widget, or even an entire 3D world. Your task is to interpret this JSON file and give a brief description of the scene.

```

# Guidelines
- Pay attention to the user request and only summarize the part of scene that is relevant for fulfilling the request. For example, suppose there are a lot of objects in the scene, among which is a bear. If the user only wants to change the color of the bear, only output information relevant to the bear.
- A child is usually a sub-component of its parent.
- The "Compiler" gameObject is a manager that contains the previously generated scripts.
- The "Main Camera" gameObject is me (the user). You don't need to include it in the description.
- If there is a child object, list the names only. Do not mention their relationship with the parent.

# Examples

## Example

User:
Request: Make the sphere twice as big
Scene JSON: sceneName:Experiments,objects:[name:Compiler,attached_scripts:Name:CreateSphere,Summary:
    This script creates a sphere in the scene.. Public fields: sphere,summmary",name:UI_Canvas,name:
    Sphere]

assistant:
Relevant object: "Sphere".

## Example
User:
Request: stop the cube from rotating
Scene JSON: sceneName:Experiments,objects:[name:Compiler,attached_scripts:Name:RotatingCube,Summary:
    This script creates a cube and makes it rotate.. Public fields: cube,rotationSpeed,summmary",name:
    UI_Canvas,name:RotatingCube]

Assistant:
Relevant objects: "Compiler", which contains the script "RotatingCube" that makes the cube rotate.

## Example
User:
Request: stop the cat from moving
Scene JSON: sceneName:Experiments,objects:[name:Compiler,name:UI_Canvas,name:cat,attached_scripts:Name
    :MovingTest,Summary: This script makes the attached object move in a circular fashion.. Public
    fields: summary"]

Assistant:
Relevant objects: "cat", which contains the script "MovingTest" that makes the cat move.

## Example
User:
Request: Create a cylinder I can pick up and paint the surface of the bathtub green
Scene JSON:

```

```

{sceneName:Bathroom,objects:[{name:bathroom02,children:[{name:toilet_bathtub_sink,children:[{name:sink_position}]}],{name:ceiling_passage},{name:lamp_cloth},{name:lamp_metal},{name:ceiling_bathroom},{name:bathroom_wall},{name:shower_light},{name:showerpanel},{name:jetspray},{name:crome},{name:faucet&handle},{name:dustbin},{name:toiletpaper},{name:bathroom_light},{name:passage_light},{name:window},{name:mirror_body},{name:mirror_glass},{name:shower_doors},{name:enclosure_body},{name:towel01},{name:handwash},{name:decoreplate},{name:towel02},{name:shower_head},{name:flowerpot},{name:plant},{name:floor},{name:artistictile_wall},{name:vanityside_wall},{name:vanitycounter},{name:sidewall},{name:towelroll},{name:dustin_by_the_toilet}]],{name:Compiler},{name:UI_Canvas}]}

Assistant:
The relevant objects are: "toilet_bathtub_sink".

## Example
User:
Request: animate the whale to flap its tail
Scene JSON: sceneName:LibraryTest,objects:[name:Compiler,name:Whale,children:[name:Armature,children:[name:Root,children:[name:Head,children:[name:Head_end],name:Spine1,children:[name:Spine2,children:[name:Spine3,children:[name:Spine4,children:[name:Tail,children:[name:Tail_end]]]]],name:TopFlipper.L,children:[name:MidFlipper.L,children:[name:BottomFlipper.L,children:[name:BottomFlipper.L_end]]],name:TopFlipper.R,children:[name:MidFlipper.R,children:[name:BottomFlipper.R,children:[name:BottomFlipper.R_end]]]]],name:Whale]]]

Assistant:
Relevant objects: "Whale", "Tail", "Spine4", "Armature".

```

Listing 4. Scene Analyzer's metaprompt

### B.3 Skill Library

```

You are given a series of skills that with simple descriptions. You are also given a user input string . You are asked to the find the skills that best fit the task in the instruction. Note that not every input needs a skill, in which case, you should output "n/a"

Here are some examples

INPUT:
skill name: MeshSize, description: If the user requests the size of the object, this is file has the function to get the renderer bounds.
skill name: CreateAnimation, description: Creates an animation that fits the clip_name for object. You should not use the animation manager if you're moving simple objects like Unity primitives.

Instruction: Create a car out of primitives

OUTPUT:
n/a

INPUT:
skill name: MeshSize, description: If the user requests the size of the object, this is file has the function to get the renderer bounds.
skill name: CreateAnimation, description: Creates an animation that fits the clip_name for object. You should not use the animation manager if you're moving simple objects like Unity primitives.

```

```

Instruction: animate the whale to flap its tail left and right, then play the clip

OUTPUT:
CreateAnimation


INPUT:
skill name: MeshSize, description: If the user requests the size of the object, this is file has the
    function to get the renderer bounds.
skill name: CreateAnimation, description: Creates an animation that fits the clip_name for object.
    Important: You should not use the animation manager if you're moving simple objects like Unity
        primitives.

Instruction: Make the car in the scene move in response to w,a,s,d keys

OUTPUT:
n/a


INPUT:
skill name: MeshSize, description: If the user requests the size of the object, this is file has the
    function to get the renderer bounds.
skill name: CreateAnimation, description: Creates an animation that fits the clip_name for object. You
    should not use the animation manager if you're moving simple objects like Unity primitives.

Instruction: Where is the top of the fridge

OUTPUT:
MeshSize

```

Listing 5. Skill Library's metaprompt

#### B.4 Builder

```

You are a code-writing assistant that is embedded in the Unity game engine equipped with a runtime C#
compiler. I will ask you to generate content in 3d environments, and your task is to write C#
code that will implement those requests. You can only respond in code that will compile in C#,
and can only add other text in inline comments, like so:
//comment
Do not put the code in a code block, just directly respond with it. That means it should not start
    with
```csharp
using UnityEngine;
but rather with just
using UnityEngine;

You are attached to the GameObject "Compiler" in the scene that also has the runtime compiler attached
    to it. Your generated C# script is automatically attached to this object and immediately
executed. Each of your output messages is compiled as a separate script. Make sure to make any
elements you might want to reuse public.

# Guidelines you **must** follow
- Each C# script should be a complete and valid class that inherits from the Widgets class.
- Each C# script should have a variable called summary that briefly describes the purpose of the
    script. Write this summary as part of the Start() function.

```

```

- Do not apologize when I point out a mistake and suggest a modification of the code you wrote.
  Only output the modified code.
- If you want to delete an existing script, use: Destroy(gameObject.GetComponent<script_name>());
- If it is appropriate to respond to my request by displaying text on the screen, use: Utils.
  DisplayMessage(message).
- If you're using UI elements in your script, create them yourself as children of the "UI_Canvas"
  gameObject.
- Avoid using raw numbers in the code. Instead, create a public class variable with the desired value
  assigned to it.
- ALWAYS make class members public.
- Only write self-contained code. Do not leave anything for me to do.
- When defining more than one classes, they should all be contained within one overarching class.
- When the Library is available, put more considerations to the descriptions that guide you on how to
  write code that uses the relevant skills.

# Utils
You have access to a Utils class that supports various functionalities.
- AddPhysics(gameObject, mass): makes the object physically realistic by attaching colliders and
  rigidbody to it
- DisplayMessage(message): Use this if it is appropriate to respond to the user's request by
  displaying text on the screen.

# Examples

## Example
user:
Scene: A scene with a cube "Cube" at the center and a cat "Cat" positioned to the left of the cube.
  The cat consists of a capsule-shaped body "Capsule". The compiler has a script called "
  CreateRandomMovingCat" which creates a cat object and makes it move around randomly.
Library: n/a
Instruction: make the cat follow the cube instead

assistant:
using UnityEngine;
public class CatFollowCube : Widgets
{
    public GameObject cat;
    public GameObject cube;
    public float speed = 5f;
    void Start()
    {
        summary = "This script makes the cat follow the cube. ";
    }
    Destroy(gameObject.GetComponent<CreateRandomMovingCat>()); //nullify the cat's previous behavior
    cat = GameObject.Find("Cat");
    cube = GameObject.Find("Cube");
}
void Update()
{
    MoveTowardsCube();
}
private void MoveTowardsCube()
{
    cat.transform.position = Vector3.MoveTowards(cat.transform.position, cube.transform.position,
        speed * Time.deltaTime);
}

```

```

}

## Example
user:
Scene: There is nothing in the scene.
Library: n/a
Instruction: Create a cube and make it draggable with mouse click.

assistant:
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.Events;
public class DraggableCube : Widgets
{
    public GameObject cube;
    void Start()
    {
        summary = "This script creates a cube that is draggable";
        // Create the cube
        cube = GameObject.CreatePrimitive(PrimitiveType.Cube);
        cube.name = "DraggableCube";
        // make the cube draggable
        cube.AddComponent<Draggable>();
    }
    [RequireComponent(typeof(Collider))]
    public class Draggable : Widgets
    {
        private Vector3 screenPoint;
        private Vector3 offset;
        void Start()
        {
            summary = "This script makes the attached object draggable with mouse click";
        }
        void OnMouseDown()
        {
            screenPoint = Camera.main.WorldToScreenPoint(gameObject.transform.position);
            offset = gameObject.transform.position - Camera.main.ScreenToWorldPoint(new Vector3(Input.mousePosition.x, Input.mousePosition.y, screenPoint.z));
        }
        void OnMouseDrag()
        {
            Vector3 curScreenPoint = new Vector3(Input.mousePosition.x, Input.mousePosition.y,
            screenPoint.z);
            Vector3 curPosition = Camera.main.ScreenToWorldPoint(curScreenPoint) + offset;
            transform.position = curPosition
        }
    }
}

## Example
user:
}

```

```

Scene: There is nothing in the scene.
Library: n/a
Instruction: Create a sphere that changes the color of any object it collides with to that of its own.

assistant:
using UnityEngine;
public class ColorChangerSphere : Widgets
{
    public GameObject sphere;
    void Start()
    {
        summary = "This script creates a sphere that can change the colors of objects it collides with to that of its own.";
        // Create a sphere
        sphere = GameObject.CreatePrimitive(PrimitiveType.Sphere);
        sphere.name = "ColoringSphere";
        // make the sphere a color changer
        sphere.AddComponent<ColorChanger>();
    }
    [RequireComponent(typeof(Collider), typeof(Rigidbody), typeof(Renderer))]
    public class ColorChanger : Widgets
    {
        // Start is called before the first frame update
        void Start()
        {
            summary = "This script makes the attached object change any object it collides with to have the same color as itself.";
        }
        void OnCollisionEnter(Collision collision)
        {
            Color myColor = GetComponent<Renderer>().material.color;
            // Get the renderer of the other object
            Renderer otherRenderer = collision.gameObject.GetComponent<Renderer>();
            // If the other object has a renderer
            if (otherRenderer != null)
            {
                // Set the color of the other object to the same as this object
                otherRenderer.material.color = myColor;
            }
        }
    }
}

## Example
user:
Scene: The relevant objects are: "Apple", "Bread", "Lettuce", "Potato", and "Tomato".
Library: skill name: MeshSize, description:
"To get the meshsize of the object, call MeshSize.GetRenderBounds(GameObject obj), which returns the total mesh bound of the parent and child gameobject."
Instruction: What is the biggest food item

assistant:
using UnityEngine;
public class FindBiggestFood : Widgets
{

```

```

private GameObject[] foodItems;
void Start()
{
    summary = "This script finds the biggest food item";
    foodItems = new GameObject[] { GameObject.Find("Apple"), GameObject.Find("Bread"), GameObject.
        Find("Lettuce"), GameObject.Find("Potato"), GameObject.Find("Tomato") };
    FindBiggest();
}
void FindBiggest()
{
    GameObject biggestFood = null;
    float biggestSize = 0;
    foreach (GameObject food in foodItems)
    {
        Bounds bounds = MeshSize.GetRenderBounds (food);
        float size = bounds.size.x * bounds.size.y * bounds.size.z;
        if (size > biggestSize)
        {
            biggestSize = size;
            biggestFood = food;
        }
    }
    Debug.Log("The biggest food item is: " + biggestFood.name);
}
}

```

Listing 6. Builder's metaprompt

## B.5 Inspector

You're a meticulous inspector who will evaluate a snippet of Unity C# code. The provided code will be automatically attached to the "Compiler" gameObject, and the Start() function for any classes defined will be executed. Note that "Compiler" contains scripts that are responsible for the behavior of objects in the scene, so it is okay for the code to try and locate the script on the "Compiler" instead of other gameObjects. You need to assess whether the provided code abides by the following set of guidelines.

- # Guidelines
- The code assigns each created gameObject a unique name. Note that this doesn't mean the variable names are unique, but rather the gameObject names are unique. GameObjects are named in the following way: GameObject x = new GameObject([Name]), where [Name] is the unique name.
- The code does not add a component in the Start() function of the class with the same name, as that creates an infinite loop. For example, if the class name is Foo, DO NOT use AddComponent<Foo>() in the Start() function.
- The code works as-is without any additional actions from the Unity editor. For example, the code should not declare a public GameObject and expects it to be filled in from the editor screen. However, it is okay for the code to declare a public GameObject but assigns them values later through code. It is only an issue if there is a public variable declared but not assigned any values.
- The following components and functions are not used: NavMesh;
- The script always inherits from Widgets instead of MonoBehaviour. You can assume the Widgets class exists.
- The script always changes the "summary" variable describing its purpose. Assume it is already declared. It is not useless.

```

- The script shouldn't contain any code outside of the main class, except statements that start with "using". Ex: "using UnityEngine;" can exist outside of the main class.
- Make sure any user input gameobjects like hands and controllers have the right names. Always refer to the UserInput string.
- Make sure there are no placeholder functions.
- Unity tags are not used.
- Unity layers are not used.

# Notes
- You can assume "UI_Canvas" always exists in the scene.
- It is always acceptable to declare variables as public, even if they are assigned values in the code

In addition, the code is allowed to use these methods from the Utils class
# Utils
You have access to a Utils class that supports various functionalities.
- AddPhysics(gameObject, mass): makes the object physically realistic by attaching colliders and rigidbody to it
- PlaceNextTo(base_obj, obj_to_place, offset): place obj_to_place next to base_obj in the direction of offset. The placement will be resolved such that the object's mesh bounding boxes do not overlap
- DisplayMessage(message): Use this if it is appropriate to respond to the user's request by displaying text on the screen.

# Output format
Your input will be the following:
Scene: ...
Library: ...
Code: ...

Where "Scene" is a brief summary of the existing objects in the Unity scene. "Library" is a relevant skill that is implemented and can be used in the code. "Code" contains the code you need to evaluate.

Your output must be in the format below:

Reasoning: ...
Suggestion: ...
Verdict: ...

Be judicious and write down your step-by-step evaluation of the code under "Reasoning", then propose how this code can be modified so that it meets the guidelines in "Suggestion". Your suggestion should be succinct. Do not include the modified code, just describe how the code should be changed. Finally, "Verdict" should be either "success" or "fail".

# Examples
## Example

user:
Scene: The scene contains only a Compiler (GameObject name: Compiler) with no attached scripts. There are no other objects in the scene.
Library: n/a
Code:
using UnityEngine;

public class CreateCube : Widgets

```

```

{
    void Start()
    {
        summary = "This script creates a cube.";
        GameObject cube = GameObject.CreatePrimitive(PrimitiveType.Cube);
        cube.name = "Cube";
    }
}

assistant:
Reasoning: The code satisfies all the requirements.
Suggestion: N/A
Verdict: Success.

## Example
user:
Scene: The scene contains only a Compiler (GameObject name: Compiler) with no attached scripts. There
      are no other objects in the scene.
Code:
using UnityEngine;
using UnityEngine.UI;

public class TimeDisplayCube : Widgets
{
    private GameObject cube;
    private GameObject canvas;
    private Text timeText;
    private bool displayTime;

    void Start()
    {
        summary = "This script creates a cube that displays the current time.";
        CreateCube();
        CreateCanvasAndText();
    }

    void CreateCube()
    {
        cube = GameObject.CreatePrimitive(PrimitiveType.Cube);
        cube.name = "TimeDisplayCube";
        cube.AddComponent<BoxCollider>();
        cube.AddComponent<TimeDisplayClickHandler>();
    }

    void CreateCanvasAndText()
    {
        canvas = new GameObject("TimeDisplayCanvas");
        canvas.AddComponent<Canvas>();
        canvas.AddComponent<CanvasScaler>();
        canvas.AddComponent<GraphicRaycaster>();
        canvas.GetComponent<Canvas>().renderMode = RenderMode.ScreenSpaceOverlay;

        GameObject textObject = new GameObject("TimeDisplayText");
        textObject.transform.SetParent(canvas.transform);
        timeText = textObject.AddComponent<Text>();
        timeText.font = Resources.GetBuiltinResource<Font>("Arial.ttf");
    }
}

```

```

        timeText.text = "";
        timeText.fontSize = 24;
        timeText.color = Color.black;
        timeText.alignment = TextAnchor.MiddleCenter;
        RectTransform textRect = textObject.GetComponent<RectTransform>();
        textRect.localPosition = Vector3.zero;
        textRect.sizeDelta = new Vector2(200, 50);
    }

    void Update()
    {
        if (displayTime)
        {
            timeText.text = System.DateTime.Now.ToString("HH:mm:ss");
        }
    }

    public void ToggleTimeDisplay()
    {
        displayTime = !displayTime;
        if (!displayTime)
        {
            timeText.text = "";
        }
    }
}

public class TimeDisplayClickHandler : Widgets
{
    private TimeDisplayCube timeDisplayCube;

    void Start()
    {
        timeDisplayCube = FindObjectOfType<TimeDisplayCube>();
    }

    void OnMouseDown()
    {
        timeDisplayCube.ToggleTimeDisplay();
    }
}

assistant:
Reasoning: This code fails because not all the classes are contained in an overarching class.
Suggestion: modify the code that all classes are contained in an overarching class.
Verdict: Fail.

## Example
user:

Scene: There are no objects in the scene.
Library: n/a
Code:

```

```

using UnityEngine;

public class CarAndPerson : Widgets
{
    void Start()
    {
        summary = "This script creates a car and a person next to it."
        CreateCar();
        CreatePerson();
    }

    void CreateCar()
    {
        GameObject car = new GameObject("Car");

        GameObject carBody = GameObject.CreatePrimitive(PrimitiveType.Cube);
        carBody.transform.localScale = new Vector3(2, 1, 4);
        carBody.transform.SetParent(car.transform);

        Vector3 wheelPosition = new Vector3(0.8f, -0.5f, 1.5f);
        CreateWheel(car, wheelPosition);
        CreateWheel(car, -wheelPosition);

        wheelPosition.z = -1.5f;
        CreateWheel(car, wheelPosition);
        CreateWheel(car, -wheelPosition);

        car.transform.position = new Vector3(0, 1, 0);
    }

    void CreateWheel(GameObject car, Vector3 position)
    {
        GameObject wheel = GameObject.CreatePrimitive(PrimitiveType.Cylinder);
        wheel.transform.localScale = new Vector3(0.5f, 0.25f, 0.5f);
        wheel.transform.position = position;
        wheel.transform.Rotate(90, 0, 0);
        wheel.transform.SetParent(car.transform);
    }

    void CreatePerson()
    {
        GameObject person = new GameObject("Person");

        GameObject body = GameObject.CreatePrimitive(PrimitiveType.Cylinder);
        body.transform.localScale = new Vector3(0.5f, 1, 0.5f);
        body.transform.SetParent(person.transform);

        GameObject head = GameObject.CreatePrimitive(PrimitiveType.Sphere);
        head.transform.localScale = new Vector3(0.5f, 0.5f, 0.5f);
        head.transform.position = new Vector3(0, 1.75f, 0);
        head.transform.SetParent(person.transform);

        person.transform.position = new Vector3(3, 1, 0);
    }
}

```

```

assistant:
Reasoning: This code creates a car with a body and four wheels, but failed to assign the body and
wheels unique names. Similarly, it forgets to assign the body and head of the person it creates
unique names.
Suggestion: assign unique names to the four wheels and body of the car, as well as the body and head
of the person.
Verdict: fail.

## Example
user:
Scene: There are other objects in the scene.
Library: n/a
Code:
using UnityEngine;

public class WaterBottleFlip : Widgets
{
    public GameObject waterBottle;
    private Rigidbody rb;

    private void Start()
    {
        summary = "This script creates a water bottle and makes it flip when the user left-clicks on it";
        CreateWaterBottle();
    }

    private void CreateWaterBottle()
    {
        waterBottle = GameObject.CreatePrimitive(PrimitiveType.Cylinder);
        waterBottle.name = "WaterBottle";
        waterBottle.transform.localScale = new Vector3(0.5f, 1f, 0.5f);
        waterBottle.AddComponent<Rigidbody>();
        rb = waterBottle.GetComponent<Rigidbody>();
    }

    private void Update()
    {
        if (Input.GetMouseButtonDown(0))
        {
            Ray ray = Camera.main.ScreenPointToRay(Input.mousePosition);
            RaycastHit hit;

            if (Physics.Raycast(ray, out hit))
            {
                if (hit.collider.gameObject == waterBottle)
                {
                    FlipWaterBottle();
                }
            }
        }
    }

    private void FlipWaterBottle()
    {
        rb.AddForce(Vector3.up * 500);
    }
}

```

```

        rb.AddTorque(Vector3.right * 500);
    }
}

assistant:
Reasoning: Even though waterBottle is declared to be public, it is assigned a cylinder later, so there
's no action required from the editor. The code thus passes all checks
Suggestion: N/A
Verdict: success.

## Example
user:
Scene: There are no objects in the scene.
Library: n/a
Code:
using UnityEngine;

public class RandomCatMovement : Widgets
{
    public float moveSpeed = 5f;
    public float rotationSpeed = 100f;
    private float timeToChangeDirection = 0f;

    void Start()
    {
        summary = "This script creates a cat that moves randomly.";
        CreateCat();
    }

    void Update()
    {
        MoveCat();
    }

    void CreateCat()
    {
        GameObject cat = GameObject.CreatePrimitive(PrimitiveType.Capsule);
        cat.name = "Cat";
        cat.transform.localScale = new Vector3(0.5f, 0.5f, 0.5f);
        cat.AddComponent<Rigidbody>().useGravity = false;
        cat.AddComponent<RandomCatMovement>();
    }

    void MoveCat()
    {
        if (Time.time >= timeToChangeDirection)
        {
            float randomAngle = Random.Range(0f, 360f);
            transform.rotation = Quaternion.Euler(0f, randomAngle, 0f);
            timeToChangeDirection = Time.time + Random.Range(1f, 3f);
        }

        transform.Translate(Vector3.forward * moveSpeed * Time.deltaTime);
    }
}

```

```

}

assistant:

Reasoning: In the CreateCat() method, the RandomCatMovement component is added to the cat GameObject,
which will create an infinite loop of cat GameObjects being created.
Suggestion: Remove the line "cat.AddComponent<RandomCatMovement>();" from the CreateCat() method.
Instead, find the GameObject "Cat" in MoveCat() and assign it to a variable, then control the cat
from this variable instead.
Verdict: fail.

## Example
user:
Scene: The relevant objects are: "Apple", "Bread", "Lettuce", "Potato", and "Tomato".
Library: skill name: MeshSize, description:
"To get the meshsize of the object, call MeshSize.GetRenderBounds(GameObject obj), which returns the
total mesh bound of the parent and child gameobject."
Code:
using UnityEngine;
public class FindBiggestFood : Widgets
{
    private GameObject[] foodItems;
    void Start()
    {
        summary = "This script finds the biggest food item";
        foodItems = new GameObject[] { GameObject.Find("Apple"), GameObject.Find("Bread"), GameObject.
        Find("Lettuce"), GameObject.Find("Potato"), GameObject.Find("Tomato") };
        FindBiggest();
    }
    void FindBiggest()
    {
        GameObject biggestFood = null;
        float biggestSize = 0;
        foreach (GameObject food in foodItems)
        {
            Bounds bounds = MeshSize.GetRenderBounds (food);
            float size = bounds.size.x * bounds.size.y * bounds.size.z;
            if (size > biggestSize)
            {
                biggestSize = size;
                biggestFood = food;
            }
        }
        Debug.Log("The biggest food item is: " + biggestFood.name);
    }
}

assistant:

Reasoning: The code goes through the food items by looking through various objects, all of which are
in the scene, and it determines the biggest item by using GetRenderBounds, which is specified as
an existing skill. The code satisfies all requirements.
Suggestion: N/A
Verdict: success.

```

---

Listing 7. Inspector's metaprompt

### C USER STUDY QUESTIONNAIRE AND INTERVIEW QUESTIONS

Rate these statements (All 1 to 7 Likert scale from Strongly disagree to Strongly agree):

- I feel frustrated when I use the framework.
- I am satisfied with the outcome of this framework.
- I was able to iteratively improve the output of my generation.
- I was able to achieve what I had in mind with this framework.
- The prompting process of creating 3D environments and objects enabled by the framework was intuitive.
- I will recommend this tool to a colleague.
- I will use this tool in my work.

Semi-structured Interview questions:

- What was your approach to prompting during this study?
- How would you compare this approach to 3D world creation to your typical experience of creating 3D environments? What was your prior experience? And how was this approach similar or different? When would you use this over your typical approach
- What were some surprising parts of this framework?
- What would you wish you could do that did not get to do? What didn't think you could do with this framework?
- What applications can you see this framework being used in?