When the Robot Surrounds Us: Co-Designing a New Human-Robot Interaction in a Full-Scale, "Robot-Room" Rapid Prototype

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***Abstract*— While robots are traditionally envisioned as physical entities that move through, sense, and act upon the environment, a new category is emerging: the inhabitable robot, or "robot-room," which redefines human-robot interaction by immersing us within the robot itself. As a first step in exploring this novel design space, we developed a *full-scale, rapid-prototyped robot-room*—not a simulation or scale model—and conducted a co-design study with 30 participants. Inside this immersive space, participants explored new forms of human-robot interaction, engaging their perceptual faculties for "knowing spaces." Our findings inform our ongoing development of a fully operational robot-room and offer valuable insights into expanding the concept of human-robot interaction to one of human-robot *cohabitation*.**

I. Introduction

When most people think of a robot, the image that first comes to mind is of a humanoid, a robotic vacuum cleaner [1], or maybe an industrial robot arm. These robots are physical things moving about in the world, making sense of their surroundings and acting in accordance. For a smaller number of people – those closer in career or interest to robotics – the image of a robot might also include robots that are *on us* or even *in us* such as robotic tattoos and implants. These robots are either not visible to us or are tiny – nearly weightless. At the other end of the scale, physically, is an emerging frontier of robotics where the robot is far from being a weightless tattoo or a familiar robot-thing like a *Roomba*, but instead *inhabitable*.

An inhabitable robot, a *robot-room*, is a room that actively, physically reconfigures to support human needs and wants. Practically, a robot-room might transform your living room into an office for remote work, or your office into an exhibition space to display your record of accomplishments to prospective clients. Psychologically, as a means of escape, a robot-room might transport you from a long day at work to a few moments on the sea, in a sail boat beneath blue skies, puffs of clouds drifting overhead. With the trend towards remote work and, generally, smaller living and working spaces, and with the stay-at-home mandate many of us endured during the pandemic, the functionality of rooms, both at home and at work, has become increasingly multi-purpose, demanding reconfigurability to meet evolving human needs and desires.

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Fig. 1. An example of reconfigurable rooms from early 20th-century architecture: two physical configurations, same view, of the Rietveld House (1924, Utrecht) showing manually movable shutters and panels dividing the space (left) and, retracted (right), opening-up the space.

Fig. 2. Our rapid-prototyped, 80 sq ft robot-room: two physical configurations, same view, supporting bedtime and playtime. The prototype is made of corrugated plastic sheets, laser-cut, suspended inside an extruded-aluminum frame.

Manually reconfigurable rooms have existed for a long time. Mechanical means of reorganizing rooms date back centuries, for example, exemplified by sliding shoji screens found in traditional Japanese homes. In the early twentieth century, the concept of the sliding screen was extended further in the canonical Rietveld Schröder House (Fig. 1). Here, wall partitions slide to close off living spaces or to open them up, almost entirely, while hinged panels open and close-off the bathroom, stairwell, and skylight, making a more or less continuous living environment. For robotics, the foundations for a reconfigurable room were advanced, notably, by Gordan Pask and Nicholas Negroponte. In *Soft Architecture Machines* (1975) [2], Negroponte's concept of a "responsive" or "intelligent" environment" echoed Pask's concept of a "reactive environment" that learns about and adapts to its inhabitant's behavioral pattern, a human-building "mutualism" [3]. Pask identified not only Negroponte but also Christopher

Alexander as among the few young design researchers who demonstrated a "credible start" toward realizing this vision of a reactive, physical environment [3]. In *A Pattern Language* [4], used by HRI researchers as a model for choreographing human-robot interaction [5], Alexander et al. offered the concept of "compressing" two or more spatial patterns into a single space, a single room, anticipating a robot-room that makes a single room, "many places."

In recent years, the building blocks for a robot-room have been developed by our group and others. Our prior work (e.g., [6], [7], [8]) demonstrated the ability to actuate rigid and flexible robot "surfaces" to achieve behaviors that physically transform rooms. To compliment such rooms, we developed robotic furnishings that function as conventional tables, chairs, room partitions, and floor lamps that, at the same time, can fetch, pick-up, and move belongings, and shape spaces in support of human activity. This work by our own research group and related work by others were considered in *Architectural Robotics* [5] (MIT Press 2016) by Keith Evan Green, a co-author of this paper, and by researchers more recently as "Human Building Interactions" [9]. Moreover, companies like Ori Living and Bumblebee (both citing Green's inspiration in [10]) have been developing highly practical, reconfigurable room systems for the market. These feature beds and storage units concealed in the ceiling or integrated into a service wall, made accessible through motorized track and pulley mechanisms. To our knowledge, no research has yet developed a fully functional inhabitable robot-*room* supporting everyday needs and wants of inhabitants – the larger ambition and focus of this paper.

But where to begin developing an inhabitable robot that serves human needs and wants? How do we begin mapping the needs and wants of people to the affordances offered by such a robot-room? We could begin by simulating the robot-room on-screen or by building a scale model outfitted with hobby electronics. However, as we are focused on developing a robot-room, a place where people live, learn, work, heal, rest, and play, it was important for us to rapidly-prototype a robot-room *at full scale*, 1:1, and invite lay people to inhabit this space with us, literally and figuratively, to responsibly discover this room "of possibilities." Moreover, we committed ourselves to a full-scale prototype recognizing that an inhabitable robot represents a novel form of human-robot interaction, an interaction where the robot is not an isolated object in space (e.g., a robotic vacuum or humanoid) nor something on or in our bodies (e.g., a tattoo); instead, this robot is *all around us* – we occupy it – which warrants placing ourselves inside the robot to better understand it, with all our perceptual faculties for "knowing spaces." To begin to understand this new space for human-robotic interaction, we report on a study that asked the question, *How do people engage with a full-scale, physical robot-room prototype?*

II. Prototype Realization

To address this question, we created a full-scale, low-cost prototype (Fig. 2) explicitly designed for this study that would be easily manipulatable by lay people, folding and pulling tendons, in an exploratory, co-design activity.

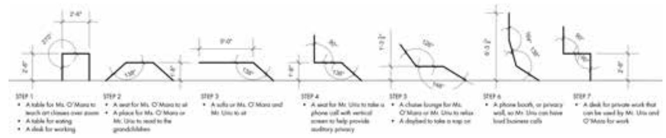

Fig. 3. We mapped the story of the couple within the confines of their small Manhattain apartment to a typology of basic configurations of hinged panels that would support them.

Fig. 4. Moving from the basic typology to room sections: here shown are three possibilities of how the robot-room might configure to serve practical needs, combined with a ceiling that serves escapist wants.

1) Conceptualization: The design of the prototype for this exploratory study was defined by three main considerations: (1) sizing the room appropriately, (2) identifying real-world needs, as a starting point, and (3) adhering to ergonomic principles.

An 80-square-foot floor area was chosen for two reasons. First, 80 square feet represents the typical minimum floor area for a bedroom under many United States building codes. Second, this dimension aligns with the average living space in densely populated urban environments, like Hong Kong where single-occupancy residences average 48 sq ft, and multiple-occupancy units, 160 sq ft. Recognizing that most individuals are unaccustomed to living in such a compact space, our team was motivated to create a 1:1 prototype enabling participants to explore this space experientially.

For serving the practical needs of a robot-room, we then mapped basic human needs of a living room drawn from [12] and [13] onto a typology of hinged-panel configurations that would support these needs (Fig. 3). We extended this preparatory work on serving practical needs to a three dimension slice through the room (figure 4), with the ceiling serving as a canvas devoted to giving shape to escapist wants.

2) Full-scale: Two walls, the ceiling, and the floor of the prototype were made from 2'x8', white, corrugated plastic sheets, scored by a digital CNC router. This scoring for the wall and ceiling panels was based on our conceptualization of the prototype, captured in design drawings shown in Fig. 3 and 4 and numerous others. Fig. 5 shows one such panel prior to mounting. For the walls and floor, altogether, there were 13 unique scoring patterns for the 16 panels. Whereas the floor and ceiling panels were scored at specific intervals, creating rigid configurations with "striated" folds, ceiling panels were scored at regular, tight intervals affording fluid, "smooth" configurations. The scored panels allowed for a wide range of panel configurations, enabling the prototype to adapt to countless room layouts, providing our co-design participants creative freedom during the co-design sessions.

Fig. 5. Photo of one 2'x8' corrugated plastic panel prior to mounting it.

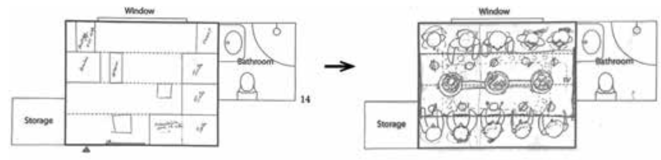

Fig. 6. Group 12's plan drawings showing reconfiguration from "casual hangout" to "dinner party." Storage and bath are outside the living space.

The structural frame of the prototype was constructed of extruded-aluminum structural members, offering a floor area of 8 foot by 10 foot with an 8-foot ceiling height. The robot-room was framing created four 2ft-wide bays, allowing columns of 2ft-wide panels to be actuated independently or in tandem to shape different room configurations. Two of the four walls in the robot-room were not paneled; these wall surfaces were dedicated to providing practical requirements: entry door, windows, kitchen services, bathroom, and closet.

In our co-design study, presented next, participants manipulated the panels, themselves and, as needed, with help from members of the research team, by pulling or pushing on panels. Pulling and pushing was facilitated by a long bar with spaced tendons (nylon threads) attached to the panels, not unlike operating marionette puppets, whereby manipulating the bar moves the hinged masses connected to it.

III. Method

Once we completed construction of the robot-room prototype, we conducted 12 co-design sessions with 30 participants that included "bodystorming" [11] activities. In 2-hour sessions, participants were introduced to the robot-room prototype, then guided through a series of group activities designed to elicit their design preferences and engagement with the space. They were asked to imagine themselves living in this space and to collaboratively brainstorm, sketch, and physically configure the room, prompted by specific scenarios drawn from [12], [13] (e.g., a study room, a bedroom, or a living room). The study utilized a think-aloud method to capture participants' thoughts and reactions in real-time, followed by the bodystorming exercise where they physically designed the environment by manipulating the full-scale prototype, thereafter acting-out activities within it [11]. The session concluded with a survey and an interview to gather insights into the participants' design ideation process, their experience interacting with the prototype, and their broader insights about reconfigurable rooms.

A. Co-design and bodystorming

We carried out a co-design activity to facilitate direct collaboration with potential users, allowing them to actively contribute to the design process [14], thereby, capturing insights that might not emerge through other design methods. The full-scale robot-room prototype lent itself well to applying bodystorming activities as part of the co-design session. Bodystorming activities invites potential users to explore, with their bodies, interactions with radical, future technologies that don't yet have existing paradigms, design spaces, or social conventions to draw on [15].

B. Participants

Using the university participant recruitment system, we recruited 30 undergraduate and graduate students (22 females, 8 males, age M=21.1) for twelve 2-hour sessions, each with 2-3 participants. Participants were compensated, choosing between a $40 gift card or 4 course credits.

C. Study Procedure

Our procedure started with obtaining informed consent and demographic information. We then presented photos showing people living in confined domestic environments (e.g. 48 sq. ft. rooms in Hong Kong) to help participants understand the context. The session had three parts: introductory brainstorming activities to facilitate participants' consideration of the room's domestic activities and space design, bodystorming activities with the full-scale Robot-Room prototype, and a "reflection interview" about the co-design experience and thoughts about reconfigurable spaces.

*1) **Brainstorming domestic activities & space in Robot-Room (40 minutes):*** Groups were initially prompted with one of three randomly selected scenarios [12], [13]: (1) "A study room you and your roommate will need to share"; (2) "A bedroom that you will use during the evening and night"; or (3) "A living room your friends will visit." Participants spent 10 minutes individually brainstorming potential activities described by the scenario. Subsequently, they were asked to consider the tools and furnishings supporting these activities, organizing these into an Activities-Tools-Space matrix. This process was designed to gradually guide participants to connect their domestic activities to the room's spatial design. Participants were then briefed on the robot-room layout to help them better understand its practical organization. Finally, as a group, participants spent 20 minutes selecting activities and hand-sketching their space-design ideas on printed floor plans (Fig. 6) and perspective views of the robot-room. Participants were also prompted to consider if they wanted to reconfigure the room into still other configuration(s); if so, they were invited to sketch those plans and perspectives. All groups designed at least two physical configurations of the room.

*2) **Bodystorming and role-playing (50 minutes):*** Participants then entered the robot-room to physically form the space. During this process, they worked together, directly manipulating the walls and floors by pulling or pushing on the hinged panels (Fig. 7). After they achieved the desired room configuration, participants were asked to role-play the envisioned activities in the configuration they created. The entire process was video recorded.

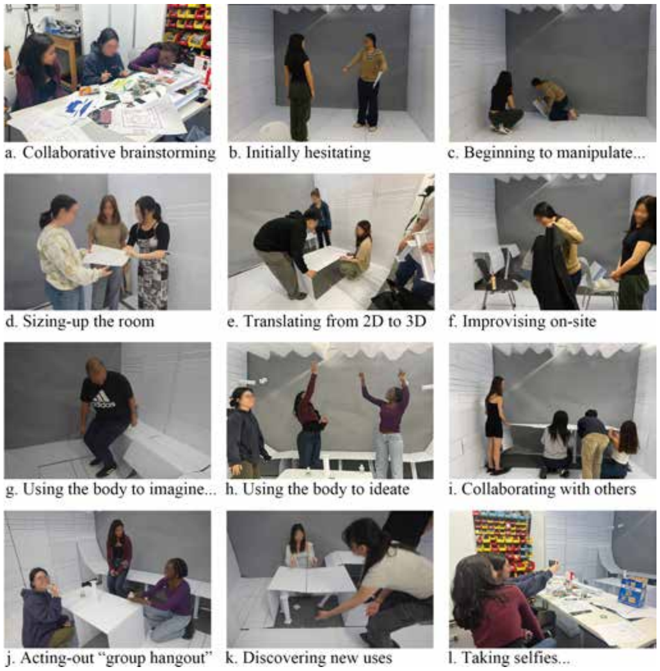

Fig. 7. Participants engaging in the bodystorming activities.

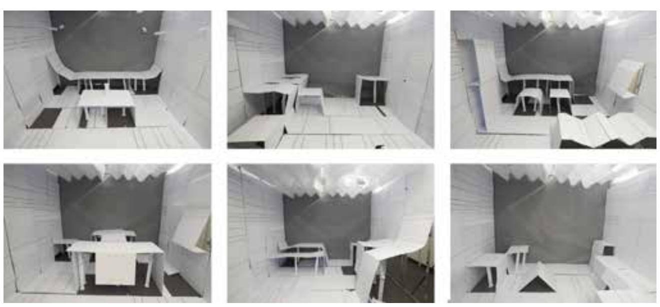

Fig. 8. Still images from video capture, showing configurations resulting from the bodystorming activity: Groups 6-8 (top) and 10-12 (bottom).

3) ***Reflecting on the co-design experience (15 minutes)***: We conducted and audio-recorded a group interview, asking participants to reflect on their design experience with robot-room, discussing its functionality, ease of use, how well the prototype allowed them to achieve their design goals, and their feeling of control over the room configurations.

D. Data Analysis

We collected data regarding the co-design process (e.g., Figures 6 and 8) and reflections on the design. Data analysis was collaborative and iterative, with three co-authors meeting twice per week over 3 months to discuss, share ideas, categorize, and reach agreement on emerging themes and insights.

To analyze the design process that participants engaged in, we reviewed the video recordings of the bodystorming activities. We investigated participants' behavior and decision-making as they interacted with the prototype. We independently reviewed the videos, using inductive coding to identify emerging patterns, and iteratively formalized a list of themes through discussions of our insights. When no more themes were identified, we independently re-watched the videos and coded the data using the identified themes. We documented a summary of our insights and then grouped the insights through discussions.

IV. Findings

The data collected encompassed many dimensions of the robot-room interaction, more than we can report here. We focus our attention on findings that most directly addresses our research question, *How do people engage with a full-scale physical robot-room prototype?*. In so doing, we report on how participants engaged with the prototype through four stages of body-storming, presented in sequence and keyed to Fig. 7, with key findings identified under them in bold type, following the initial "Collaborative Brainstorming" activity.

A. Initial Hesitation

When participants first entered the prototype, the unfamiliarity led to initial hesitation, even after being briefed on it (Fig. 7b). For example, P9 in Group 4, upon walking to the center of the room and examining the floor plan, turned to the research assistant and asked, "Do I just, like, pull on this thing?" This uncertainty was also evident in Group 10, where participants stood in the center, looking around the room and at the research assistants, seemingly waiting for guidance. We interpret this initial hesitation to the novelty effect [16].

B. Beginning to Manipulate the Boards

After overcoming their initial hesitation, once they understood how the boards could be manipulated, most participants eagerly explored different configurations independently (Fig. 7c). For example, in Group 1, participants collaboratively experimented with folding the boards, with P1 asking, "Can we fold this piece down?," followed by P2 suggesting, "We can fold this floor piece this way, too!" This hands-on experimentation led to dynamic interactions, as participants discovered new ways to manipulate the prototype. Notably, P3 in Group 2 deviated from expectations by removing an entire board from the wall and flipping it 90 degrees, demonstrating creativity and a willingness to push the boundaries of the prototype's intended use. This suggests that interaction with the prototype spurs explorations and divergent thinking as participants become more comfortable with it.

C. During the Process of Making Configurations

As participants engaged more deeply with the prototype, they used their bodies to translate their 2D designs into 3D spaces, gaining a better understanding of spatial dimensions and functionality. Below are key observations taken from this "Process of Making," organized as six headings in bold type.

Understanding the Actual Volume of the Room (Fig. 7d). Through direct interaction with the prototype, many participants began to realize that the room's size differed from their initial perception. For example, in Group 4, P10 remarked, "This room is a lot smaller than I thought." This

Fig. 9. Participants interacting with our full-scale, inhabitable prototype to understand scale, explore, improvise, and role-play envisioned activities supported by their configuration-making.

suggests that interacting with a physical, room-scaled prototype allowed participants to develop a clearer understanding of spatial scale and dimension as they adapted their designs to the actual constraints of the space.

Translating Design from 2D to 3D (Fig. 7e). The process of translating designs from 2D plans to 3D space required participants to reconsider and adjust vertical arrangements. In Group 2, for example, participants gauged the height of a board against the wall, with P3 lowering it while P4 suggested, "Can we make the bed higher? [lifts board] because I don't think we want the board that low [chuckles]... so it can [store] stuff." Our full-scale inhabitable prototype permitted the participants to gain an understanding of spatial depth and vertical dimension about their designs.

Improvising (Fig. 7f). We observed that the prototype served as a tool for improvisation, allowing participants to explore new design ideas in-situ. For example, Group 6 imagined a reading light integral with the wall, debating its placement and functionality: "Maybe...a reading light on this side...but I don't know if that would replace the lamp.... [It] might look awkward...if it's coming out of the wall."

People also improvised with the things found in our lab. In Group 1, P1 decided to create a "fidget corner" using cloth. They also incorporated a whiteboard from the lab when they realized it was not possible to pull down the ceiling boards: "We can use the whiteboard as a room divider…". This adaptability suggests that physical co-design encourages spontaneous creativity and problem-solving.

Using the Body to Imagine Real-Life Scenarios (Fig. 7g). We also observed participants using their bodies to role-play real-life scenarios within the prototype to enhance their understanding and communication of how their designs would function in everyday use. In Group 2, P5, looking at the brainstorming sketch as a guide, gestured and offered, "We can put some books, iPad, laptops here; makeup and all that stuff [here]" [gestured to the desk], or pull out here [kneeling down] towels on those hooks." This example of embodied interaction helped participants visualize the practical application of their designs and refine their configurations based on how they imagine their bodies moving within the space. As P29 in G12 offered, "I think the [bodystorming] definitely gives you a sense of scale. Before I had no idea what a table for 10 people felt like; it [was] kind of fun...to have the table really...appear in front of you. Now you have that scenario, that picture in your head becoming real, even if it's kind of a low fidelity." The participants' use of their bodies and the things found around our lab during the design activity suggests the potential of exploring room-scaled interactions via our full-scale inhabitable prototype.

Using the Body to Ideate Spatial Dimensions (Fig. 7h). Participants also used their bodies to gauge the dimensions of the space, making on-the-spot decisions about the size and placement of furniture configured from the panels. In Group 1, P1 assessed the height of a desk by physically measuring it against the prototype, suggesting, "Let's each take half of that." Similarly, in Group 4, P9 and P10 discussed the size of a potential shelf, with P9 gesturing its approximate size, while P10 stepped aside to visualize how it would fit in the room: "But I don't know...because it's like this [gesturing]." p9: "Maybe it could be like this here [gestures to show the approximate size of a shelf and its location]." p10: "Could be small, right?" This tactile engagement with the prototype was crucial in helping participants align their designs with the realities of the physical space. By physically engaging with the prototype, participants visualized, communicated about, and refined their configurations, illustrating how embodied interaction could deepen spatial understanding and support practical, real-world design decisions.

Collaborating with Other Participants (Fig. 7i and l). The bodystorming process required collaboration, as multiple participants often needed to work together to hold panels, attach velcro, or adjust board lengths. This collaborative effort facilitated social interaction, allowing participants to learn more about each other and share insights, which arguably facilitated a rich exploration of the robot-room.

D. After the Configuration is Built

After the configuration was built, participants not only reflected on their design choices but began to actively imagine how the space would function in their daily lives. The physical prototype allowed them to embody future activities, which led to deeper exploration of how they could adapt or further modify the space to suit evolving needs and wants.

Acting Activities on the Physical Prototype (Fig. 7j). After building their configurations, participants further imagined how they would use the space in real life. For example, in Group 7, participants discussed using the space for activities like working out and yoga: p18: "And then [points to floor space] we're working out here." [P19 mimics a couple of squats.] p18: "Are we doing yoga?" P17: "Yeah, and we should put, like, a nice comfy bed [gestures to the location of the bed]." This role-playing suggests that participants associated their designs to their daily routines by making the experience more tangible and relatable.

Discovering New Uses for the Space (Fig. 7k). The completed configurations often inspired participants to discover new uses for the space that they hadn't initially considered. In Group 12, P30 pointed to a gap between tables, suggesting it could serve as place to place a potted plant: "I guess in

Fig. 10. Photos of our first working, robotic-room panel system.

this case you could just put like a flower pot or tall plant or something? It could still be useful."

V. Discussion

Through a co-design activity, we explored how people engage with a full-scale, physical robot-room prototype [14]. This approach revealed insights that might have been missed with conventional methods like scale models or simulations. We learned how people collaborate, improvise, and use their bodies (Fig. 9) to understand an inhabitable robot. Our study suggests that physical interaction spurred exploration and divergent thinking about a new category of HRI. The bodystorming activity enabled users to engage with radical technologies without being confined by existing paradigms or conventions [15]. Finally, this study shows how people connect with the robot in ways that reflect their lives, echoing Alexander et al.'s final "pattern," "Things from Your Life," where people shape environments with what matters to them: "the things you care for, the things that tell your story" [4]. Our full-scale, rapid prototype allowed participants to readily share their HRI story.

VI. Current and Future Work

Building on the exploratory co-design outcomes reported here, as well as insights from our prior research on robotic surfaces (already cited), we have initiated the development of a full-scale version of the inhabitable robot-room's panel system (Fig. 10) that features multiple panels, moving along a rail, actuated by a combination of tendons, scissor mechanisms, linear actuators, and motors. The panels can support the weight of inhabitants engaged in daily routines, such as walking, sitting, sleeping, playing, and lounging. Currently, the panels are capable of actuation and rudimentary control, allowing the system to achieve configurations that participants identified as practical and desirable. Through iterative cycles of design, fabrication, and testing with users, we aim to expand these efforts toward fabricating and user-studying the full-funtioning robot-room, incorporating sensing capabilities and refined control mechanisms.

VII. Conclusion

In this paper, we introduced a new category of robot where the robot *surrounds us* – we occupy it. We then described a full-scale rapid-prototype and reported the results of a co-design activity whereby groups of participants helped us understand this emerging design space for HRI. This work provides a foundation for a new form of human-machine interaction, where the machine envelops us — a robot "consummated," as Walter Benjamin says of architecture [17], "in a state of distraction." Our work is an early-effort to extend human-robot *interaction* to what can now be characterized as human-machine *cohabitation*, with the potential to accommodate – in a smaller footprint – the increasingly "post-human condition," characterized by new forms of productivity and play, longer life expectancy, mass migration and urbanization, and an environmental crisis.

Acknowledgments

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