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THE POWER OF PROTOTYPES IN FORESIGHT ENGINEERING

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ABSTRACT
Prototyping has long been a popular method in engineering and design practice. The continued use of physical prototyping is based on its strength in helping teams to make ideas tangible, iterate quickly at a low cost, and develop a shared language. Over the past seven years, our team has used prototyping in an industry-research program focused on foresight engineering—the development of new products and services that are three or more product cycles in the future. Through the discussion of three international cases drawn from India, Europe and the United States, this paper offers insight into the value and application of physical prototypes earlier in the innovation process and before the traditional handoff from strategy to product design. In summary, physical prototypes are exemplary tools for envisioning complex systems, serving an unmet need in helping teams explore potential service applications, and helping reveal the path of progression from today's solutions to tomorrow's opportunities.

Keywords: prototyping, foresight engineering, innovation, system design, service development

1. INTRODUCTION
One of the toughest challenges faced by companies is developing an ability in long-range innovation, tying the company's vision for the future to the ongoing search for opportunities. The reality is that engineering research and design practice needs to start building the future today, which places undue pressure on design engineers and researchers to take action about the unknown. This area of industrial practice is called Foresight Engineering, and it focuses on the ongoing development of new products and services that are three or more product cycles in the future. In research conducted over the past seven years, we have studied the use of physical prototypes in foresight engineering for capturing and communicating a team's opportunities inside the organization, connecting the company's vision and strategy with the day-to-day work of engineering design teams, and helping the teams to connect vision to research to engineering design. By extending traditional prototyping practice to a strategy and foresight domain, and adding insights into the prototypes from these fields, the foresight engineering prototype gain additional power as a tool that can be used across the entire organization, and across the entire process of innovation.

2. PROTOTYPING IN ENGINEERING PRACTICE
The continued use of physical prototyping in engineering design practice is based on its strength in helping teams to make ideas tangible, iterate quickly at a low cost, and develop a shared language. Within the design literature, Carleton [2], Houde and Hill [6], and Schrage [9] have provided well-written accounts of physical prototyping in practice at different stages of development. While prototyping has a long history in the conceptualization and modeling stages of the innovation process, tangible prototypes that are intended to represent real opportunities have rarely existed in the fuzzy front end, much less at the vision stage [1].

2.1 Gap at the Fuzzy Front End
As the name suggests, the fuzzy front end of innovation describes the beginning of new product development, a period often characterized by high ambiguity, inquiry, and creativity. Activities typically include idea generation, idea evaluation, user ethnography, market strategy, and product

visioning. During this early stage, prototypes have received minimal attention in literature or industrial practice. Surprising little is understood about the application and culture of physical mockups and prototypes. The majority of prototyping studies focus on applications of sketching, software development, user interfaces, and even student creativity [2]. Physical prototypes are usually built on paper as two-dimensional forms, and only a handful of studies have addressed applications in three-dimensional (3D) forms. In addition, culture plays a critical role in shaping designer beliefs about prototyping value and use, and less is understood about external influences and environmental factors that foster the initiation and development of prototypes. Ten years ago, Schrage noted that, "the great ethnographies of simulation and prototyping culture have yet to be written" [9], and relatively little has been investigated in the design literature even in recent years. Schrage's observation is especially galling given his overly expansive definition of prototyping to encompass virtual simulations, process storyboards, and scenarios. Houde and Hill analyzed multiple technology cases to propose a model of prototype use in industry [6]. They found that most cases occurred during the conceptual design stage of a project; interestingly, they also described several examples that occurred earlier in the development process. Their study hints at the existence of prototyping during the fuzzy front end, and based on our research, we posit that prototyping provides tremendous benefit during the earliest stages of innovation.

2.2 Engineering Design in a Broader Context

Engineering design is characteristically described as part of a product development process, which begins with product or project definition [11]. Carleton sampled a wide array of industry practitioners building physical, three-dimensional prototypes, correlating their usage with accepted models of new product development practice [2]. Her findings can be seen in Figure 1, which demonstrate that physical prototyping typically begins with specification definition.

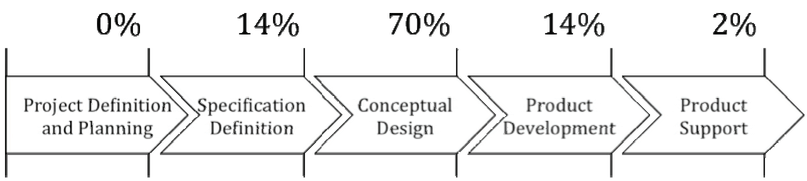

Figure 1. Occurrence of physical, three-space prototypes built at different stages of new product development practice [2]

In reality, the process of engineering design does not start in isolation, and in practice, several other stages precede it, notably market strategy and research. When Figure 1 is placed within a more comprehensive model of innovation development, as displayed in Figure 2, the use of prototyping quickly becomes circumscribed. By putting the first model in the context of a larger process, specifically linking new product development with the earlier stages of corporate visioning [7] and research and strategy [8], then it appears that prototyping offers limited value, or at least, is rarely used before project definition. This interpretation raises an interesting research question. Are engineering designers less likely to work comfortably in the fuzzy front end, are there application limits to the prototyping method, or are different types of prototypes possibly required for early-stage innovation? Anecdotally, earlier work has showed a lack of awareness about the benefits of prototyping during the fuzzy front end. Our team began to explore the problem deeper to see what comprised a coherent, thoughts-to-things model of engineering.

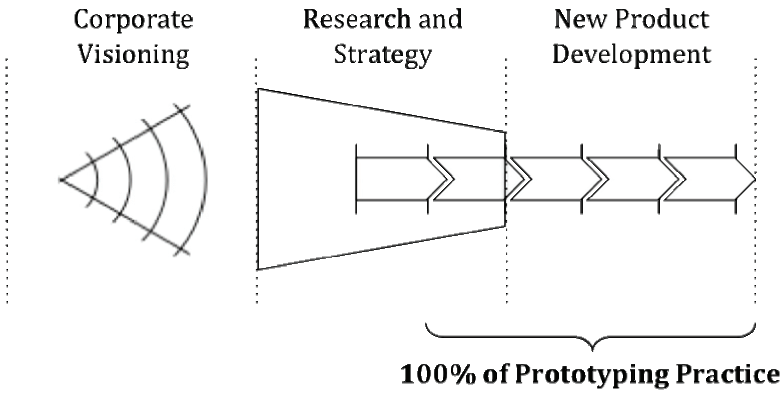

Figure 2. The occurrence of prototyping practice in context of the standard model of corporate innovation comprised of corporate visioning, research and strategy, and new product development. Note that all prototyping efforts have been documented during the latter stages in the process.

3. STANFORD PROGRAM IN FORESIGHT ENGINEERING

In recent years, the Stanford Center for Foresight and Innovation (CFI) has worked with various industry partners to develop an integrative model of innovation within Stanford's Schools of Engineering and Humanities and Sciences. This work was started as a direct response to industry's request for new theories, models, and tools that could better enable foresight engineering. Foresight engineering is an area of practice that trains technical innovators, including engineering researchers and designers, how to think, plan and build long-term, specifically new products and services that are three or more development cycles in the future. CFI has developed a model of foresight engineering that connects the three primary stages of innovation end-to-end: corporate visioning, strategy and research, and new product (service) development. The CFI model has become the nexus of an emerging global innovation network of research groups, universities, and companies around the world.

3.1 Foresight Engineering Methods

As part of this model, an integrated set of foresight engineering methods – what one might call a pattern language for innovation – has been developed, which allows practitioners to move quickly from theory to application [3]. This methodology has been designed to help practitioners to: (a) think about the long-term, (b) communicate the long-term, and (c) bring the long-term into day-to-day work. Together, these three values help our partners "know where to begin when starting to build the future," as one of our senior industry partners told us. These words echo those of visionary inventor Walt Disney, who noted the first question his teams always asked when starting a new development process was "Where do we begin?" [5].

CFI adopted prototypes as a foresight method due to the importance in making long-range ideas more tangible. As described earlier in the paper, prototypes have a well-understood value within the later stages of engineering design. CFI's goal was to encourage physical prototyping in the earlier stages of the innovation process as part of foresight engineering. In CFI's executive education programs and university workshops, three types of prototypes have been introduced and experimented with, specifically: paper mockups, critical function, and dark horse, all of which have a deep history in Stanford's Department of Mechanical Engineering.

3.2 Paper Mockups

Paper mockups are three-dimensional physical prototypes made from paper and other inexpensive materials. Often considered low resolution by computer scientists, paper mockups are intended to be rough models that embody and explore a particular design concept. The proverbial example is a paper airplane, which might be constructed as a fast experiment in wing flap shape. Paper mockups may be built at any stage of the engineering design process. At Stanford, graduate students specializing in engineering design must complete a team assignment to build (and ultimately race) functioning bicycles crafted from paper, cardboard, tape, and other everyday objects. This design exercise helps expose the students to the basic principles of prototyping, requiring low commitment and ensuring rapid cycles of feedback and learning.

3.2 Critical Function Prototype

Critical function prototypes are three-dimensional physical prototypes that are built to experiment with one dominant product or service feature in the overall solution. By considering which feature might be serving as the critical function, designers are forced to prioritize and reflect on the solution components, as well as the integration and interaction between components. Critical function prototypes are valuable because they focus thinking and help reduce the likelihood of the kitchen sink syndrome (also known as feature creep). When thinking about solutions in the future, a common danger is to over-engineer and address all potential issues, and team efforts are often most effectively directed at resolving one particular thorny issue.

3.4 Dark Horse Prototype

The third prototyping method plays a significant role in the outcomes of foresight engineering prototypes. Dark horse prototypes are three-dimensional physical prototypes that are built to explore a previously rejected idea. In the world of horse racing, a dark horse is a bet that has the least likely odds to win, but which ultimately may have the greatest chance of reward. Likewise, designers may have rejected certain ideas because they were perceived as being too risky, radical, impossible, unacceptable, and so on. The dark horse prototype gives designers the permission to think bigger and more creatively. In practice, a dark horse prototype is an iteration of an existing prototype. What CFI has found is that designers often dismiss their earlier intuition and gut sense, and the early ideas often become more predictive of the final success of the project deliverable than subsequent iterations.

Dark horse prototyping has seen very little discussion in prior literature, despite its use among Stanford's industrial partners since the late 1990s. The concept of the dark horse prototype was brought to our attention by Professor Mark Cutkosky of Stanford University's Mechanical Engineering Department in January 2000. As part of an industry sponsored, year-long engineering design course, Prof. Cutkosky realized that students often became enamored of the prototypes they built, to the point that they narrowed their solutions too early in the design process. Prof. Cutkosky explained, "The 'dark horse' was added … to help preserve ambiguity (keep the design solution space from shrinking too fast). It asks teams specifically to invest some time on a prototype that uses a concept or technology that they did not seriously consider in the [previous quarter]" [4].

4. THREE CASES OF FORESIGHT PROTOTYPING

The remainder of the paper describes three cases of foresight engineering prototypes developed by industry leaders in India, Europe, and the United States. These cases are drawn from recent CFI work in order to help raise awareness about the effective use of prototypes in foresight engineering and the potential application to complex system design, service development, and long-range planning. All prototypes were developed as part of CFI executive education programs, which provided a controlled situation to observe and document participant behavior. In all cases, participants were accomplished technical leaders and senior managers in their respective fields. Participants, although familiar with the benefits of prototyping for engineering modeling and production, generally had not considered prototyping for earlier stages in innovation. As a result, participants were ideal naive subjects. During each workshop, participants were taught the same foresight methods and then encouraged to build physical prototypes to present a long-range solution that they believed was three or more development cycles in the future based on their industry. They could choose the idea and form of the prototype. Our objective was to elicit feedback about the group's learning process and document all reflections [10].

4.1 Case 1: Complex System Design

The first case is from an international heavy industry conglomerate based in India. Over time, the conglomerate has become a national leader in industries as diverse as tractors, automobiles, energy, and food distribution. The agglomeration of multiple industries under one umbrella is not uncommon in India. The explicit cooperation between different divisions of this particular Indian company was high, owing to the company's long history and roots before the establishment of India's democracy. Perceptions about long-term change and adaptability were interesting to observe in the participants. When a company has thrived longer than the current system of government – including the government agencies responsible for supporting regional infrastructure, transportation, health systems, and energy distribution – a successful company would need to understand and solve many of these critical interlinked problems in order to prosper over time.

4.1.1 Beliefs About Prototyping

With this rich history, participants had a desire to address complex problems that, by their nature, would play out over the long-term in a chaotic world. They also hoped to approach these problems in a sustainable manner. The participants involved were comprised primarily of advanced technical leaders, who had been trained to reinforce all assumptions with statistics and trend data. When they transitioned to building long-range prototypes, the experience was both liberating and confounding. Once adjusted, these participants proved to be one of the most imaginative groups CFI has worked with to date. Through the construction of physical prototypes, the participants envisioned a model of a highly complex solution for a future food system in India, as shown in Figure 3. This model showed a high-level view of multiple relationships required for a complete seed-to-mouth regional food system.

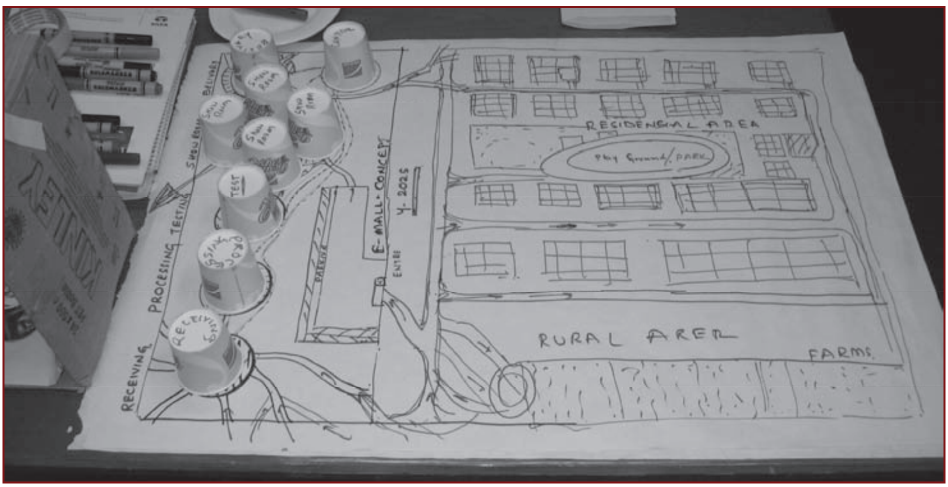

Figure 3. A paper mockup for a complete seed-to-mouth Indian food system comprising multiple companies, consumers, products, and services for 2023

4.1.2 What Participants Learned

Paper mockups seem deceptively simple; however, the benefits can be remarkable. The exercise in prototyping channeled group energies into creating a future solution grounded in reality and historical data. Instead of being a far-fetched vision, the team's mockup of a complex system addressed limitations in existing technologies and services. At the most rudimentary level, participants saw that tangible prototypes more effectively facilitated their group discussion and their abilities to communicate a new abstract idea to potential partners and users outside the group. Prototypes often formalize design thinking as polished artifacts. Now with a rough mockup under discussion, the focus shifted from specific aspects of production and delivery to the inherent assumptions in the idea.

As the workshop facilitators encouraged participants to self-reflect, additional observations came to light. The Indian participants began to realize that long-range prototypes serve as visual analogies. For example, a piece of string could represent a wireless network. Participants also discovered that prototypes help embody and convey the critical questions in a system that cannot be answered today. As more information might be gained about the larger problem, they could return to their prototypes over time with fresh eyes. Lastly, seeing a physical mockup of their idea also validated the actual timeframe of the solution. If every piece of the prototype already exists today, then is this really the future? Perhaps some of the solution was not as far in the future as participants imagined. This final learning was the most inspirational, sparking intense discussion about what participants could begin doing as a company today.

Interestingly, while each participant had led programs developing various components of the proposed future food system, and despite the fact that they had spent endless hours as a group integrating their individual thoughts into one solution, the foresight prototype allowed them to actually see the larger system they envisioned in its full complexity. Across multiple dimensions – including tractor manufacturing, seed distribution, transportation, processing, consumer experience, and purchasing – of the solution, participants felt empowered to tell stories about the larger system that extended from the company's current long-range plans. Instead of simply allowing potential opportunities to "hang in the air" and remain unvoiced, team members instead began building additional pieces for inclusion in their joint prototype, annotating different parts of the larger model, and recording several long-range, unanswerable questions that would ultimately drive individual initiatives in their company's research and development (R&D) programs.

4.2 Case 2: Service Development

The second case concerns a Northern European transportation company that was transitioning from being a product-centric company to being a product and services integrated company. Its products and services immediately enter a complex and dynamic ecosystem, and due to the company's technical expertise, management often found itself taking the lead on many industry-changing initiatives.

4.2.1 Beliefs About Prototyping

The need to plan long-term was already embedded deeply within the company, as well as the practice of engineering prototypes. Due to the long development lead required for its primary product lines, the company's product strategy was unusually well defined, and participants were most interested in understanding possible service solutions. They did not have a particular timeframe in mind for their solutions, but instead desired a continuous spectrum of ideas in order to maintain an industry leadership position. One team built a foresight prototype, shown in Figure 4, of a future transportation system. At the core, the solution proposed a network of security and safety services across multiple countries, tying multiple groups together with advanced sensing and telecommunications technologies.

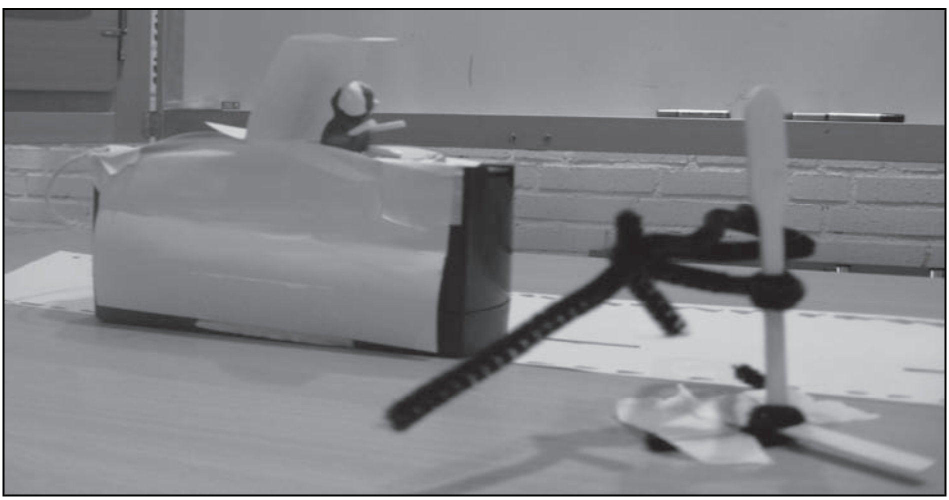

Figure 4. The dark horse iteration of a foresight engineering prototype for a security and safety transportation service with accompanying technologies for 2020

4.2.2 What Participants Learned

Similar to the Indian participants in the first case, the European team used their prototype to see the complexity of the system they were creating, also noting the important long-range questions that could not be answered in today's framework. They were able to note at which points partner companies would likely be brought into the solution and when the company's research divisions would need to provide answers in order for the system to develop fully. Through the activity of building, participants realized that their solution would unite vast networks of individuals within an informal and just-in-time information system, and the ultimate benefit would make transportation drivers more aware, perceptively safer, and ultimately happier in the driving experience.

As the prototype developed, the team replaced the proverbial bullet points and corporate slideshows to show a dynamic service solution in action. Others outside the team, many of whom were from other divisions in the company, quickly saw the potential value of the solution and responded with enthusiastic questions and suggestions. Now with more input, the team was able to begin evaluating in-house technologies currently in development, expected improvements from planned product acquisitions, open questions that would face various internal R&D groups, and missing areas of competence. With the bigger picture in mind, participants could also identify which areas would require breakthroughs in basic science, critical knowledge they would need for long-range planning.

As an unexpected source of delight, they discovered that their solution addressed a tremendous problem in the client base today. This delight often results from building a dark horse prototype. In this case, participants repositioned the service in terms of the user of today – as opposed to the user in the future. They discovered that their service could take advantage of a large expected change in national demographics. During the discussion, they used human figurines made of colored clay to represent their client base, where different colors represented different generations and demographics. Of all the upcoming demographic changes, the most critical change would become the eventual forced retirement of one group of current users based on European law. Planning for this specific date in the mid-term future, participants began treating those colored figurines a bit more gingerly. They began to ask themselves: with all we know about this client group, is there something else we can do to continue leveraging their knowledge, beyond simply removing them entirely from the future system?

Participants soon realized that the current group of users could play a support role for future users – a need that already existed, and which the team had not considered until they built the prototype. When describing the first prototype, they had focused on the group of the future users. For the dark horse iteration, they moved the figurines representing the current users into a newly created, critical role for the future service. They made this swap with full awareness of demographic timing and factors outside of the company's control. This insight let participants understand that not only can the progress of technologies be mapped, but also the progress of social and societal changes for the development of new services.

4.3 Case 3: Connecting the Short- with Long-Term

In a third case, a well-known American software provider used the foresight methods to explore multiple paths to the future, building on current strengths and technical expertise. The participants were eager to learn the various methods in order to integrate and apply them to their own R&D efforts. Comprised primarily of engineers and project managers, the company has a "show me" mentality that participants brought to all opportunities. While this mentality allowed them to be highly focused and analytical, it also made them skeptical about imagining bigger and unexpected possibilities long-term.

4.3.1 Beliefs About Prototyping

Participants adopted foresight prototypes quickly based on prior experience with two-dimensional efforts, such as sketching, in their daily work. Before building physical 3D prototypes, participants were asked to develop extensive perspectives of the future, which occurred at different time horizons. It was interesting to observe the importance of multiple timeframes. The company's product portfolio, although largely based in software, was comprised of a broad collection of tools and services ranging in development from three to seven years. This situation matches CFI's previous experience with other industrial partners. Most large companies must plan a spectrum of time horizons for their foresight prototypes as part of a comprehensive innovation portfolio.

4.3.2 What Participants Learned

A team of participants first prototyped a technology solution for 2015 built around concepts of social networks strongly evident in American youth, also known as the Millennial generation (born between 1985 and 2004). The premise was that networks of friends would share their recommendations about neighborhoods and real estate, similar to what they were already doing today through social networking tools. Technology would begin emerging from the company's research center in seven years to support this networking. The team was satisfied with their long-range idea because it met the clear criteria of a future solution: it factually could not exist today because the underlying technologies simply did not exist yet.

Then, we surprised the team by challenging them to build a dark horse prototype, shown in Figure 5. Suddenly empowered, the team removed the props representing the people, who had been tied together with yarn as a social network. In a flash of inspiration, the team connected the yarn to the objects around the people as a separate network. The team described how the objects had social knowledge about the other objects, independent of the people, and this knowledge could then better support the decision-making of the people in the network. As social objects, any new houses for sale would be able to sense if their behavior would affect neighboring houses; in other words, the network of houses mirrored the same sensitivities, grudges, and emotional qualities that affect human friendships.

Figure 5. The dark horse iteration of a foresight engineering prototype for a socially aware and connected neighborhood in 2015

In this case, participants had started prototyping by concentrating on current technology gaps and existing assumptions about how people interact. By re-focusing their thinking through the dark horse prototype, they broadened their perspective and found a more ingenious solution. As importantly, participants began to link actions today with tomorrow's opportunities. In other words, they could see what steps to take next along a path that would bring the proposed solution to fruition in the far future. The American participants ended the workshop energized from what they learned by prototyping.

5. CONCLUSION

In all three cases, design engineers and other technically trained managers built various prototypes before the formal commencement of new product development. They used the prototypes to help conceptualize and plan long-range strategy. Many of them already held senior roles in corporate strategy or regularly contributed to the development and execution of their respective company's strategy. While initially uncomfortable prototyping in the fuzzy front end, all participants adapted quickly and spoke at length about the benefits of applying a familiar method in a new context. It is remarkable when a long-used and seemingly well-understood design method finds new use. By placing prototypes for foresight engineering within a broader context, our hope was to share more examples from a range of companies and applications. This has been a frequent request voiced by CFI partners from both industry and academia, and we felt others may also be interested in recent learning.

We encourage additional studies to explore the use and value of prototyping beyond traditional engineering design and new product development. For example, what additional applications of prototyping exist, and do applications differ by industry? What other design methods are used to explore long-range solutions? How does organizational culture affect the adoption of prototyping in the fuzzy front end? Do early-stage prototypes help transfer organizational learning across different groups and across multiple stages in the innovation process? What is the effect of rough mockups and physical prototypes on long-range planning and technology strategy?

This paper offers a first glimpse of prototyping at the earliest stages of foresight engineering and innovation. Our ongoing research has begun to lay the foundation for a better understanding about the tools and processes needed to develop better long-range innovations.

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