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Customizable, Reprogrammable, Food Preparation, Production and Invention System

Final Report

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Icosystem Corporation: NIAC Phase I FINAL REPORT

This document is the final report for Icosystem's Phase I NIAC project, titled "Customizable, Reprogrammable, Food Preparation, Production and Invention System."

Executive Summary

With the prospect of increasingly long space missions, the requirement for appropriate provisioning and crew nutrition becomes critical to mission success. Food has a direct impact on the physical and mental well being of astronauts, but also has significant implications in terms of transportation, storage, preparation and disposal. For this project, we proposed to develop a revolutionary system for food preparation in space. The proposed system allows astronauts to create familiar or novel foods from a set of basic ingredients, through a series of processing steps designed to achieve a vast selection of textures and flavors. The system takes into account hard constraints (such as nutritional content and limitations in preparation processes) as well as the subjective preferences of astronauts.

Since the beginning of our Phase I effort, the Icosystem team has focused on accomplishing the following:

- Designing a software prototype, meant to demonstrate how Interactive Evolutionary Computing can be used to explore a space of possible foods.
- Assembling an advisory panel of domain experts from the various areas touched upon by our project, including space mission experts, food experts, and other specialists who could contribute to the project.
- Organizing a workshop held on January 12, 2006, and to be attended by these advisors. At this workshop, we demonstrates our process for exploring a potentially vast space of foods starting from a fixed set of ingredients.
- Exploring hardware options that would allow us to begin producing food combinations in the nearer term.
- Compile and analyze workshop results.
- Use workshop results to develop a roadmap for future work, and a plan for a possible Phase II proposal

Project significance

Our work has the potential to provide a number of key breakthroughs relative to current and developing technology.

- First, crew members will be able to design their own custom meals daily. These meals might emulate familiar food items, or they may be completely novel forms of food. In fact, one critical contribution of our approach is the discovery and creation of previously unknown food flavors and textures.
- Similarly, any food difficult or impossible to create due to the constraints of space travel (e.g. anything that requires fresh produce) could have its taste, texture and appearance precisely emulated using the standardized base (phoneme) ingredients.

- Our technique makes it possible to take into account nutritional constraints, ensuring that astronauts are following a healthy and appropriate diet.
- By developing a standardized set of “building block” ingredients, our technique will simplify the logistics of selection and delivery.
- The use of a single machine can also dramatically reduce the need for storage – removing the requirement of individually pre-packaged meals.
- The food production technique can also significantly reduce waste, again by removing the requirement for individually packaged meals.

With the prospect of missions of increasing length, all of the advantages listed above will become increasingly significant for the space program. The results of our work thus have the potential for a dramatic reduction in operational complexity and substantial savings, while improving crew health and morale.

The proposed technology for food creation has implications beyond the space program. Any type of long-term mission will benefit from this technology, both in terms of crew well being and in reducing transportation, storage and waste handling requirements. Furthermore, the ability to create novel foods could have significant commercial value in the consumer world.

Background

The physical and psychological impact of food in space

Food is a key element of physical and psychological health for crews of space missions and other long-term missions, as summarized nicely in the following quote by Jack Stuster in his book, *Bold Endeavors* (Naval Institute Press, 1996):

> *Food is the quintessential habitability issue, whether onboard a wooden ship locked in the polar ice, a commercial airliner, or a spacecraft.*

Generally speaking, food becomes more critical as the length of missions increases. For space missions, there is a qualitative difference between short missions, such as space Shuttle missions, and long missions such as those on the International Space Station (ISS). From the physical standpoint, along with exercise and aerobic conditioning, food is critical in allowing astronauts to sustain body mass and reduce bone loss. These factors become significant for missions lasting over one month. Psychologically, food also comes to play a major role in long missions, a finding that has been observed during arctic missions, historical sailing expeditions and submarine missions.

There are several reports of astronauts experiencing “taste changes” during space missions. In the case of short missions, the reports are mostly anecdotal in nature, as the flyers are still adapting both physically and psychologically when they return to earth. More systematic observations of long-mission flyers reveal various forms of psychological compensation, including for example the “camping effect,” whereby simple foods that may not seem appealing under normal earth circumstances acquire a greater appeal during the long missions, just as a can of spam may seem like a gourmet treat during a camping trip.

In the last decade, two distinct incidents during extended space missions have highlighted the importance of food. In 1997 an American astronaut participated in a mission on the Russian space station *Mir*. Because of a late crew substitution, it was not possible to do a food manifest substitution and the replacement was constrained to consume the food that had been prepared for the original astronaut. Owing to substantial dietary differences between the astronauts, the replacement astronaut ended up losing approximately 30 pounds of body mass in a 4-month period, and reported significant effect on his morale.

In October of 2004, one American astronaut and one Russian cosmonaut began Expedition 10 to the ISS. The mission commander, Dr. Leroy Chiao, is one of the advisors on our proposed project. According to Dr. Chiao, when the Expedition 10 crew arrived onboard they discovered that over 90% of the food containers for their mission had been opened by crew members from Expedition 9. The prior expedition had experienced a food shortage through an apparent combination of high food consumption rates and an unbalanced resupply ship manifest. The crew requested and received permission to open Expedition 10 food containers. The crew was asked to report what was taken so that the crew of Expedition 10 could make up the shortfall on their vehicle. However, miscommunication led to significant underestimation of the amount of food that had been consumed or replaced. As a result, about five weeks into Expedition 10, the crew realized there was a significant food shortage problem. By instating a careful rationing plan and using candies and dessert to make up for caloric deficits, the crew was able to keep the physical impact to a weight loss of between 5 and 10 pounds for each crew member. However, the shortage took a psychological toll on the crew members, and required careful mission management and interpersonal skills to avoid a more dramatic impact. The crew members were able to keep a positive public face during ground communications, and overall kept a positive attitude, using humor to cheer each other up. Dr. Chiao also rationed out treats to keep up morale, and organized the rationing to include hot meals at the end of workdays. Thanks to these efforts, the crew members were able to maintain a positive attitude until the resupply ship arrived on Christmas day. This experience strengthened the observation that food is extremely important for crew morale and well being.

Space food hardware

The American, Russian, Japanese and European space agencies all have programs on space food, albeit with different approaches. The Japanese and European agencies make special, ethnic foods for their astronauts. The foods are manifested for launch on either American or Russian transport vehicles for missions that include European or Japanese crew members. The American space program tends to rely heavily on commercial foods and thermostabilized pouches similar to the "Meals Ready-to-Eat" (MREs) used by the military. Thermostabilized pouches are supplemented by custom-made freeze-dried foods and by "bonus containers" for long-duration flights, which can contain commercial food items that are approved by NASA food experts. The Russian space program in contrast tends to rely more on canned food and freeze-dried food, but all foods are custom-made. Some commercial bonus items are also allowed by the Russian space program.

Preparation of food in space is limited by a number of technical and safety constraints. No actual cooking is done in space, with the food preparation equipment being limited primarily to machines that can process the canned or freeze-dried provisions. The Space Shuttle includes a hydration station with hot or cool water for freeze-dried packages, as well as a convective food warmer. The Russian Soyuz spacecraft has no food warmer and no hot water, so that all food items must be eaten cold, and no freeze-dried food is used. The ISS includes a Russian hot or warm hydration station with an adapter that accepts American food packages, a Russian conductive warmer for canned food, and an American conductive warmer for U.S. food packages.

Space food research today

Although there is general understanding within NASA of the importance of food for space missions, only those astronauts who have experienced long-duration space flights can really understand and appreciate the impact of food on long missions. The food shortage experience of ISS Expedition 10 has increased the level of awareness of NASA managers on the importance of food. Although currently NASA is still highly Shuttle-centric, and thus focused on shorter missions, there is an increasing realization of the importance of planning for longer missions. The Russians, on the other hand, seem to have a superior understanding of the importance of space food as a result of their more extensive experience with long-duration missions on the Mir space station and the ISS.

In general, food specialists have done a good job of offering menu variety while operating under the limitations of the available food preparation hardware and other constraints. However, beside from the addition of some menu items, space food has not changed substantially in the last 15 years. As the US space program embarks on longer space missions and consider the possibility of lunar and Martian missions, food will only become more important.

Phase I accomplishments

During Phase I we performed the following tasks:

- We assembled a panel of domain experts from the various areas touched upon by our project, including space mission experts, food experts, and other specialists who could contribute to the project.
- We organized a workshop to brainstorm approaches to this project and to help guide our research. The workshop enabled us to share our expertise with representatives from a variety of relevant disciplines, and to elicit their feedback.
- We began a feasibility analysis for putting many different food-processing technologies into a single machine. We started to identify an intermediate set of processing equipment that will allow us to produce food combinatorially in the shorter term.
- We began addressing the issue of mapping out the space of all possible foods, as well as trying to discover the best way in which to explore that space. We created a software prototype that provides a mechanism for exploring a subset of food space: a database of existing recipes.
- We presented our results at the Annual Fellows meeting in Atlanta, GA.

These accomplishments are described in more detail in the sections that follow.

We have also been able to generate visibility for our project: since the award of our Phase I contract, our project has been featured as the cover story of the August 18, 2005 issue of *New Scientist*, and it was mentioned as part of a cover story in the May issue of *Fast Company*.

Assembling an advisory panel

The initial motivation for our participation in the Phase I project was our strength in the area of “interactive design” and our interest in the problem of space food. However, we did not have in-house domain knowledge in some of the key areas associated with this project. For this reason, and on the advice of our Phase I proposal reviewers, we made a concerted effort to assemble a team of experts in a variety of relevant fields, including:

- Former/current astronauts with long term mission experience
- Chefs who have experimented with novel food combinations and preparation mechanisms
- NASA space food experts
- Food scientists
- Rapid prototyping hardware specialists

Biographical sketches for the individuals who have advised us during Phase I are listed below.

Dr. Leroy Chiao – Former Astronaut

Dr. Chiao has extensive experience as a NASA Astronaut and prior to that, as a Research Engineer. He is currently involved in business ventures and is applying his vast aerospace and engineering expertise to both the commercial and academic sectors as a Consultant and Public Speaker. In August 2006, he will begin an appointment in the Mechanical Engineering Department at the Louisiana State University as the first Raborn Distinguished Chair Professor.

Dr. Chiao recently left NASA following a fifteen-year career with the agency. A veteran of four space missions, Dr. Chiao most recently served as Commander of Expedition 10 aboard the International Space Station. He has logged over 229 days in space - over 36 hours of which were spent in Extra-Vehicular Activity (EVA, or spacewalks).

A native English speaker, Dr. Chiao also speaks Russian and Mandarin Chinese. He has flown space missions and worked closely with Russian, Japanese and European Astronauts and their affiliated space agencies. Dr. Chiao is uniquely qualified to speak about the United States, Russian, Japanese, European and Chinese Space Programs. A Space Station Commander and Space Shuttle Mission Specialist, Dr. Chiao is also a certified Co-Pilot of the Russian Soyuz spacecraft. He is an expert in all facets of U.S. and Russian EVA hardware and operations, and is EVA certified in U.S. and Russian spacesuits, tools, and training programs.

Dr. Chiao studied Chemical Engineering, earning a Bachelor of Science degree from the University of California at Berkeley in 1983. He continued his studies at the University of California at Santa Barbara, earning his Master of Science and Doctor of Philosophy degrees in 1985 and 1987. Prior to joining NASA in 1990, he worked as a Research Engineer at Hexcel Corporation and then at the Lawrence Livermore National Laboratory.

Homaro Cantu – Executive Chef at Moto Restaurant, Food Innovator

After training in Charlie Trotter's kitchen for three years, Chef Trotter gave Homaro the opportunity to work in his dining room with some of the country's most respected service members. After learning the art of fine wine and table service, Homaro was promoted to Sous Chef and re-entered the kitchen. With a strong passion for Asian minimalism and worldly ingredients, Moto offers the perfect canvas for Homaro and his team to explore his ideas. For Homaro, cooking consists of a mixture of delicate food preparations and mechanical ingenuity. Homaro maintains a very simple philosophy toward what he calls food engineering --to create is not to copy-- and if creating requires new tools, Homaro has been known to invent those as well. His creations include maki roll sushi, which looks and tastes like fish and seaweed, but contains neither, and is created using a Canon i560 inkjet printer.

Dr. Malcolm Bourne - Emeritus Professor of the department of food science and technology at Cornell University

Dr. Bourne joined the Cornell Faculty in 1962 and became Emeritus Professor of Food Science (Active) in 1995. He taught a graduate level course in food rheology at Cornell from 1973 through 1985 and the course Food Science 447 "International Postharvest Food Systems" from 1977 through 2001. Prior to coming to Cornell he worked in the food industry for ten years. He spent two years on the Cornell-University Philippines project in Los Banos, Philippines helping establish a Department of Food Science. He has been on short-term assignments in a number of countries in Asia, America, Europe and Russia. He is Editor-in-Chief of J. Texture Studies. The Institute of Food Technologists gave him the International Award in 1992 and the American Association of Cereal Chemists the Scott Blair Award for food rheology in 1993. He is a Fellow of the Institute of Food Technologists, Institute of Food Science and Technology (UK), Australian Institute of Food Science and Technology and an Inaugural Fellow of the International Academy of Food Science and Technology. He is serving as President of the International Academy of Food Science & Technology 2003 to 2006.

Dr. Charles Bourland – Formerly of NASA's Food Technology Commercial Space Center

Charles Bourland received his BS, MS, and Ph.D. from the University of Missouri at Columbia. His doctorate was in food science and nutrition. He began work at the Johnson Space Center in 1969 with Technology Inc, later Krug International, and now part of Wyle Labs. Dr. Bourland was involved in the food and package development for Apollo, Tektite, Skylab, Food for the Elderly program, Apollo-Soyuz, Shuttle, Shuttle/Mir, International Space Station, and planetary bases where crops will be grown and processed for food. He retired from NASA in December 1999 after 30 years of developing food systems for space. He was the subsystem manager for International Space Station food in the Flight Crew Support Division at the Johnson Space Center. His responsibilities included food and package development and advanced planning for International Space Station, and Advanced Life Support involving conversion of chamber grown crops to edible food. Dr. Bourland worked part time as a consultant to the NASA Food Technology Commercial Space Center at Iowa State University from 2000 to 2005 and taught a class entitled "Living and Working in Space" at the University of Houston Hilton College of Hotel and Restaurant Management from 2002 to 2004. In 2000 he received the Snoopy Award, the astronaut personal achievement award and in 2003 he was honored with a Faculty Alumni Award from the University of Missouri.

Harold McGee – Food Scientist and Writer

Harold McGee writes about the chemistry of food and cooking. He took up this unusual vocation after studies at the California Institute of Technology and at Yale University, where he wrote a doctoral thesis with the prophetic title "Keats and the Progress of Taste." In 1984 he wrote and published On Food & Cooking: The Science & Lore of the Kitchen, a 680-page compendium that brought feature articles in Time and People Magazines and won the Andre Simon Memorial Fund Book Award in Britain. In 2004, after working on it for ten years, Harold published the second, completely revised edition of On Food & Cooking. Along the way he has contributed reviews and original research to the scientific journal Nature, and has written articles for many publications, including The New York Times, The World Book Encyclopedia, The Art of Eating, Food & Wine, Fine Cooking, and Physics Today. He has lectured on food chemistry at the Culinary Institute of America and other professional schools, the Canadian Federation of Chefs and Cooks, at universities, the American Association for the Advancement of Science, and the American Chemical Society. He has appeared on CNN and on National Public Radio's "All Things Considered," "Fresh Air," and "Science Friday." In 1995 he was named to the James Beard Foundation's Who's Who in American Food.

Dan Goldwater – Squid Labs

Dan Goldwater has several years experience as an engineer and architect in the software, hardware, chip and networking industries. Most recently at the MIT Media Lab, Dan developed autonomous swarming robot technology, low-power lighting devices, 3D spatial tracking technology and more. As a Distinguished Member of Technical Staff at AccuRev Inc, he developed a commercial software server core and novel methods for software development coordination and efficiency. Dan was Systems Architect at Adero, where he led the development of global web caching services. Dan was a Senior Component Engineer at Intel, working on the Pentium 3 and Celeron 2 projects. Dan has Bachelor's and Master's degrees in Electrical Engineering from Brown University.

Dr. David Julian McClements – Professor of Food Science UMass. Amherst

Dr. McClements studies the molecular-colloidal basis for the physicochemical and physiological properties of foods and their components, such as their texture, flavor, appearance, shelf-life and nutrition. A better understanding of this subject will enable food scientists to design and manufacture high-quality healthful food products in a more systematic and cost-effective fashion. Particular research projects include: (i) utilization of interfacial engineering to improve emulsion stability to environmental stresses and to develop novel encapsulation and delivery systems; (ii) characterization of interactions between dietary fiber and surface active lipids in order to develop cholesterol reducing foods; (iii) improvement of freeze-thaw stability of emulsion-based food products; (iv) study of influence of ingredient interactions on food properties. He received both his Bachelor of Science (Hons) and his PhD in Food Science from the University of Leeds, UK. He received the Samuel Cate Prescott Award for Outstanding Ability in Research in Food Science and Technology, Institute of Food Technologists, USA, 1999 and the Young Scientist Award, Agricultural and Food Chemistry Division, American Chemical Society, USA, 1996.

Additional Advisors

Dr. Hervé This – Food Chemist

Hervé This (pronounced "Tees") is a physical chemist on the staff of the Institut National de la Recherche Agronomique in Paris. He is a longtime collaborator with the famed French chef Pierre Gagnaire, and the only person to hold a doctorate in molecular gastronomy, a cutting-edge field he pioneered. Bringing the instruments and experimental techniques of the laboratory into the kitchen, This uses recent research in the chemistry, physics, and biology of food to challenge traditional ideas about cooking and eating. He is the author of several books about food and cooking, including *Molecular Gastronomy*, his first work to appear in English, which includes discussions on the physiology of flavor, how the brain perceives tastes, how chewing affects food, and how the tongue reacts to various stimuli.

Dr. Jeffery Hoffman – Former Astronaut

Dr. Hoffman's original research interests were in high-energy astrophysics, specifically cosmic gamma ray and x-ray astronomy. His doctoral work at Harvard was the design, construction, testing, and flight of a balloon-borne, low-energy, gamma ray telescope. Selected by NASA in January 1978, Dr. Hoffman became an astronaut in August 1979. Dr. Hoffman served as a support crewmember for STS-5 and as a CAPCOM (spacecraft communicator) for the STS-8 and STS-82 missions. Dr. Hoffman has been the Astronaut Office Payload Safety Representative. He also worked on EVA, including the development of a high-pressure spacesuit, and preparations for the assembly of the Space Station. Dr. Hoffman was a co-founder of the Astronaut Office Science Support Group. During 1996 he led the Payload and Habitability Branch of the Astronaut Office. Dr. Hoffman left the astronaut program in July 1997 to become NASA's European Representative in Paris, where he served until August 2001. In August 2001, Dr. Hoffman was seconded by NASA to the Massachusetts Institute of Technology, where he is a Professor in the Department of Aeronautics and Astronautics. He is engaged in several research projects using the International Space Station and teaches courses on space operations and design.

Dr. Hod Lipson – Assistant Professor Mechanical andAerospace Engineering, Cornell University

Hod Lipson is an Assistant Professor at Cornell University's School of Mechanical & Aerospace Engineering since 2001. He is also on the faculty of Computing & Information Science and a member of the graduate fields of Computer Science and Computational Biology at Cornell. Prior to this appointment, he was a postdoctoral researcher at Brandeis University's Computer Science Department and a Lecturer at MIT's Mechanical Engineering Department. He received his PhD in 1998 from the Technion - Israel Institute of Technology. Lipson's research interests are in the area of biologically-inspired Artificial Intelligence for design automation and robotics. Before joining academia, he spent several years as a research engineer in the mechanical, electronic and software industries.

Dr. Michele Perchonok – NASA Advanced Food Technology Lead Scientist

Dr. Perchonok is a Food Scientist and research lead at NASA's Johnson Space Center. She has extensive experience designing and researching food for space, including a number of research projects into growing and processing food for longer term space missions, and extra-planetary missions. Her previous research includes work in bulk ingredient based menu development, shelf life determination of thermally processed foods, and thermostabilized food development. She also has experience researching the psychological impact of food and food variety in space.

Workshop overview

We organized a workshop, held on January 12th 2006 and attended by members of our advisory panel. The purpose of the workshop was to brainstorm approaches to this project and to help guide our research. We also developed a prototype software tool to illustrate our process for exploring a potentially vast space of foods starting from a fixed set of ingredients, as described in a later section. The workshop enabled us to show the technology to experts from relevant disciplines and to elicit their feedback. In the remainder of this section we summarize the presentations and discussions that took place at the workshop.

Psychological and technical challenges of food in space. Presented by Dr. Leroy Chiao

At the workshop, Dr. Chiao spoke about his own experiences with food in space, as well as about the more general psychological factors associated with food on long and short duration space missions. In particular he discussed the food shortage he experienced as part of ISS Expedition 10, and the resulting changes in behavior he and his crewmate went through, as well as the overall impact on their psychological state and morale. Chiao also discussed the different attitudes towards food found between short and long duration astronauts, with the long duration astronauts placing a much greater importance on food quality, variety and availability, which parallels the experiences of long-duration crews in other extremely isolated environments, such as historical sailing expeditions and Antarctic expeditions. Finally, he discussed the food technologies currently used by NASA and other space agencies, such as freeze dried foods, thermostabilized pouches, and canned foods, including their advantages, disadvantages and preparation methods.

Novel food preparation and production techniques. Presented by Homaro Cantu

Chef Cantu's presentation focused on the novel food preparation techniques used in his Chicago restaurant, Moto, and how they could potentially be applied to making food for space. Some of the more relevant techniques included edible paper and packaging materials, polymers that increase food storage life, highly focused cooking via laser beams, and cooking within extremely insulated containers. Cantu also presented a number of novel food storage and delivery methods, such as preserving fruits and vegetables by forced carbonation, as well as utensils with built-in food delivery systems. Similarly, he presented a number of "inflatable" desserts, which can be stored highly compressed, but inflate through various simple chemical reactions. Finally, he presented a number of foods cooked via extreme cold, rather than heating.

Long-term and short-term hardware possibilities Presented by Dan Goldwater

Dan Goldwater presented an overview of thoughts related to the creation of a universal food fabrication machine. This included considering the raw material constraints and automation factors. He also reviewed the state-of-the-art in rapid prototype manufacturing technologies including how those technologies might be applied to edible materials and the technologies' limitations. Technologies covered included Fused Deposition Modeling (FDM), Droplet Printing, and 3D printing using a powder and a binder (such as using a Z Corp 3D printer). Goldwater also briefly touched on other advances that might occur in the next 25 years which would considerably change the perspective on creating a universal food fabrication machine. A more detailed summary is provided in a later section.

Discussion – Food in Space

This discussion focused primarily on the domain-specific constraints of preparing food for or in space. The group felt that the issues of greatest concern to NASA with respect to food were garbage, shelf life, weight and safety. Safety issues in particular were discussed in detail, since the number of cooking methods that might be available in space are limited by numerous safety factors, such as maximum and minimum temperatures and allowable emissions. The group felt that the greatest challenges would be to make the machine easy to use, easy to maintain, and easy to clean. Finally, many panel members felt that it might be potentially easier and preferable to make new, interesting and tasty foods, rather than attempting to replicate faithfully existing earth foods.

Presentation and Demo of the IEC Technology. Presented by the Icosystem Team

The Icosystem team discussed interactive search, how it has been applied in the past, and how it could be applied in the food space. The recipe search prototype presented later on in this report was demonstrated to the workshop participants, as well as a number of other Interactive Evolution-based applications. A number of scientific issues related to interactive search in the food space were also presented, including user fatigue, defining the components of a food grammar, creating software that can learn to recognize "good" or "interesting" foods, and learning and adapting to individual user preferences. Finally, the inverse problems of discovering new foods that can be made from a known set of ingredients, combinations and transformations, and discovering which ingredients, combinations and transformations are necessary for recreating a known food, were also discussed.

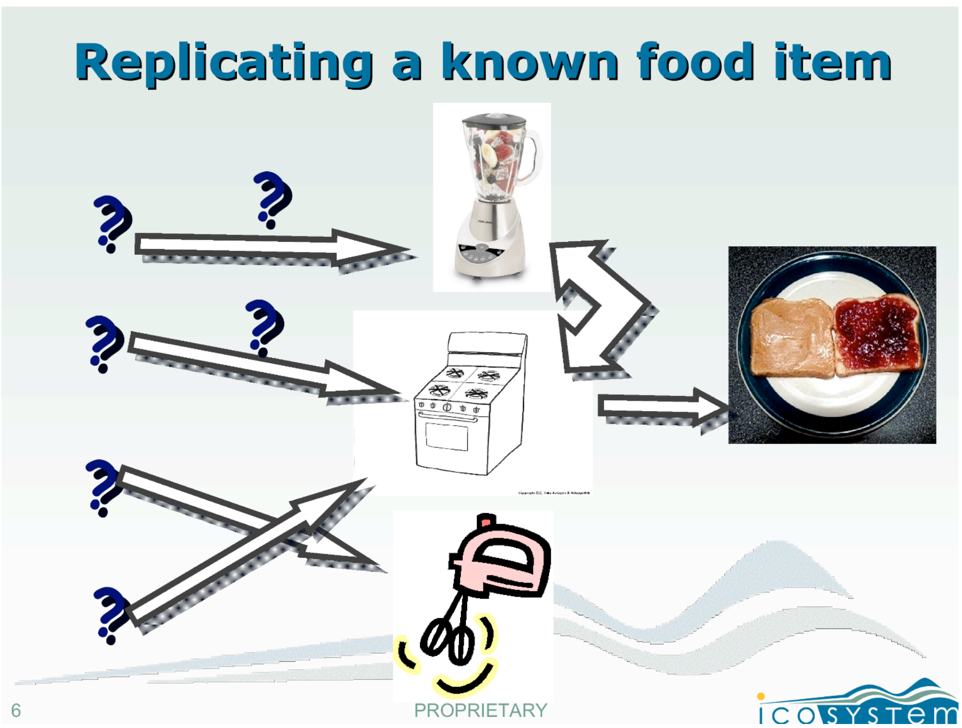

Figure 1. What ingredients and transformations are required in order to replicate a known food item?

Figure 2. What new food items can we create, given a known set of ingredients and transformations?

Discussion – Where do we go from here?

This discussion centered on directions to take this research, including reasonable goals and focus areas for a potential Phase II grant. Key suggestions included focusing our efforts on describing variants of a relatively simple and well-understood food, such as bread, or simple milk products (e.g. cream, butter, yogurt). In this case the main effort would be in developing the food grammar and making sure that it could successfully be translated into a process leading to the correct food products, and in describing/creating variations in texture (or possibly flavor) within the smaller space defined by the known food item. Alternatively, it was also suggested that we could focus on creating a single simple new food (e.g. something similar to a power bar), and giving it a variety of textures and flavors. Again, the focus would primarily be on the feasibility analysis and software development, with some potential food production using already existing technologies such as 3D printing. Overall, there was a strong consensus with regard to focusing on software and feasibility proofs in the near term, and on focusing on problems related to food shelf life, garbage reduction, and storage size reduction.

Technologies for food creation

It is not enough to have a generative language capable of describing any food texture: we must be able to execute the phrases in that language, in order to produce the described food item. While our ultimate goal is a machine that is fully automated, loading itself with ingredients, and reconfiguring itself in response to broad meal requests (e.g. roasted chicken and green beans), this sort of machine is still many years in the future.

In our original proposal we identified as a medium-term objective the development of a device consisting of a re-configurable combinatorial network of pipes (the network's edges) and functional chambers (the network's nodes) that perform the food transformations, and into which elementary or composed ingredients would flow.

As a step toward investigating the design of such a machine, during Phase I our collaborators from Squid Labs carried out a search of existing technologies for 3D printing. They identified several technologies that could be adapted to food creation:

- **Fused Deposition Modeling** (FDM) is one method to develop rapid prototypes or models. FDM is a proprietary technique commercialized by the company *Stratasys*. The FDM machine builds the part by extruding a semi-molten filament through a heated nozzle in a prescribed pattern onto a platform. A second nozzle may extrude a second material if required. When the first layer is complete, the platform lowers by one layer thickness and the process begins again. The part is easily removed from the platform, supports are removed, and the part is ready. Currently FDM only works with plastic materials, but it may be possible to replace the plastic materials with certain types of food ingredients.
- **Droplet printing** is the technique used in inkjet printers. Relevant to this proposal is the work of Chef Homaro Cantu at the Chicago restaurant *Moto*. Chef Cantu attended our workshop and has agreed to serve as an external advisor during Phase II. Using a Canon i560 inkjet printer, he is able to prepare sushi rolls that look and taste like sushi, but contain no seaweed or fish. Chef Cantu prints images of sushi rolls on pieces of edible paper made of soybeans and cornstarch, using organic, food-based inks that he invented. He then flavors the back of the paper, which is ordinarily used to put images onto birthday cakes, with powdered soy and seaweed seasonings. Chef Cantu has developed other innovative techniques for food preparation, some of which may be applicable to food preparation during space missions (described later).
- **Powder+binding printing** is a technique commercialized by *Z Corp*. In this modified inkjet printing technology, layers of powder are a printed on top of one another. The printer head dispenses a solution to bind the powder together in a desired pattern. At the end of the printing process, the unfused powder is swept away, leaving a hardened, 3D item. Z Corp's 3D printers currently use a plaster powder, but it may be possible to modify them to use other materials, such as food ingredients.

While none of these technologies is immediately applicable, they provide some inspiration for possible future designs.

Software Prototype: Searching recipe databases

As mentioned earlier, Icosystem has developed a software prototype, meant to demonstrate how Interactive Evolutionary Computing can be used to explore a space of possible foods, which was presented at our January 12th workshop. In order to create a fully functional prototype within the Phase I time frame, we focused on a specific subset of our overall problem – rather than exploring the space of all possible foods, our initial prototype provides a mechanism for exploring a database of existing recipes, based on user preferences, ingredients, nutritional requirements and other constraints. The recipe database we are working with was provided by a commercial recipe search tool- Recipe Manager.

Users enter a set of ingredients they have available into our tool, as well as other possible criteria, such as course (e.g. entrée, dessert) and the tool visually presents them with a population of possible dishes containing those ingredients. By right-clicking on the image of a given dish, the user can get further information about it, including the complete list of ingredients, cooking directions, and potentially other information such as total preparation time and a nutritional summary. The user can then select his favorites among the presented dishes, and these favorites are used to guide the next round of search. The tool continues to present new populations of recipes to the user, evolved from the user's choices in the previous round for as long as the user wishes to continue their search. Screenshots of the tool we have developed are provided in the section below.

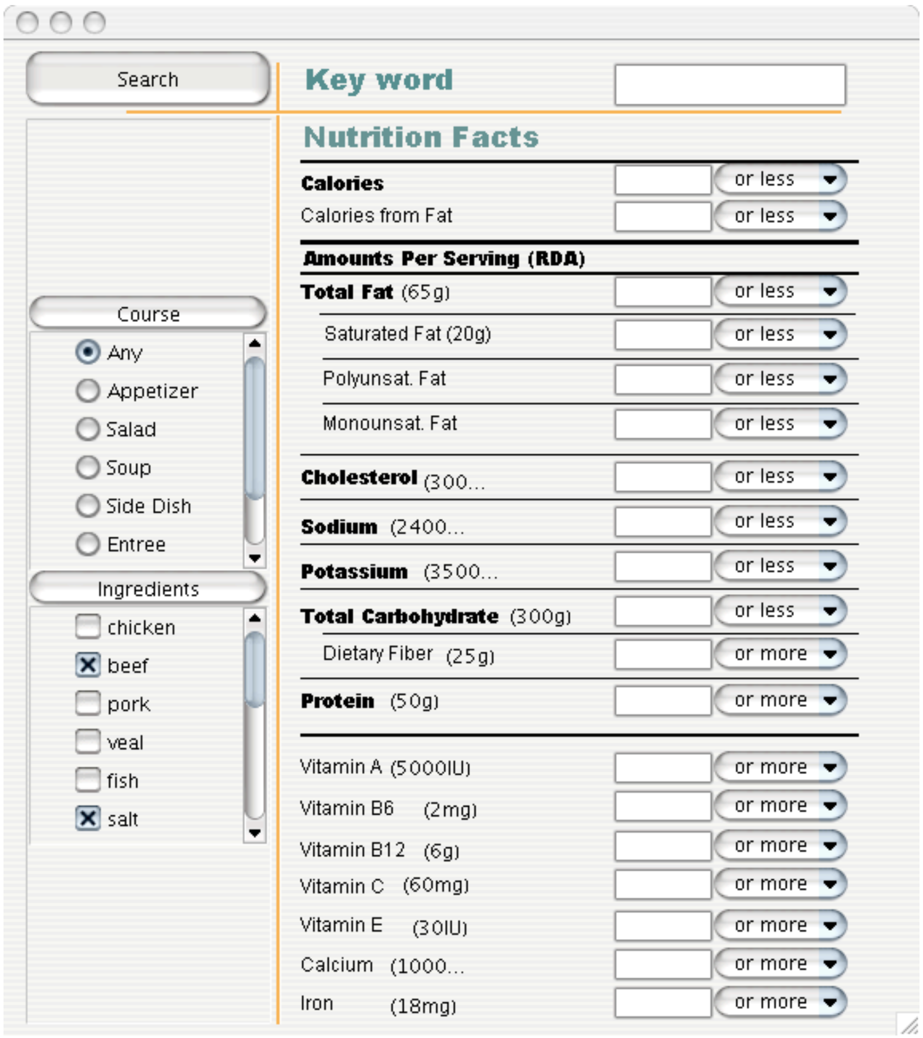

Figure 3. The Initialization Window. The user can specify their explicit requirements for the recipe search here, including nutritional requirements. In this case, the user is looking for recipes that contain beef and salt. This is a flexible interface that allows other constraint categories (e.g. origin of food, cooking method) to be added to the search window as needed.

Figure 4. Search Results. Our Interactive search tool begins finding recipes containing the search ingredients. The Recipe Manager logo is currently being used as a placeholder for recipes with no associated image. We are evaluating other, more informative display options.

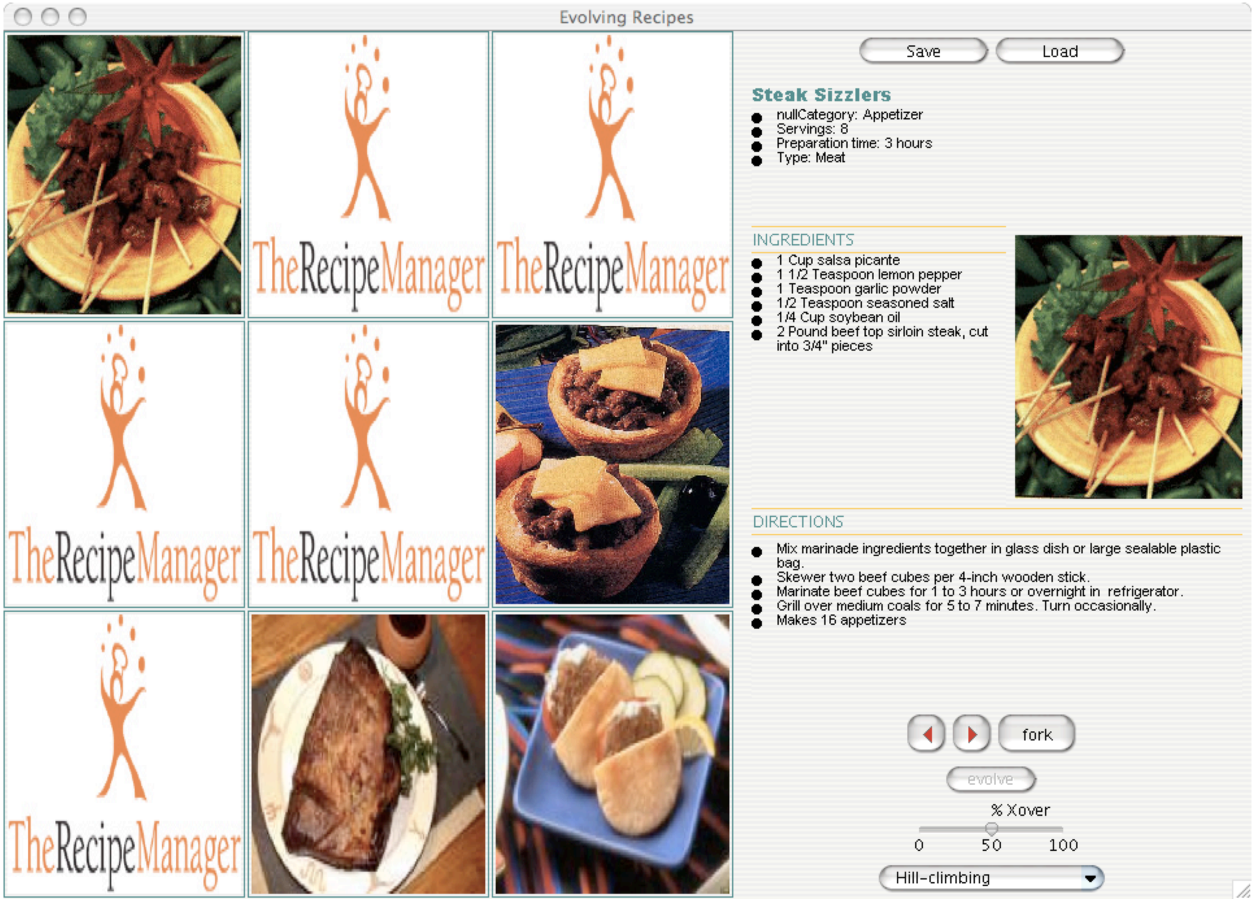

Figure 5. The user can see details of any recipe by right-clicking it with the mouse. The user can select recipes by left-clicking on them. Their genotype (including ingredients, nutritional information, cooking method etc.) will be used to generate the next generation of recipes. Here, the user has selected the steak sizzlers recipe for evolution (the recipe information is displayed on the right).

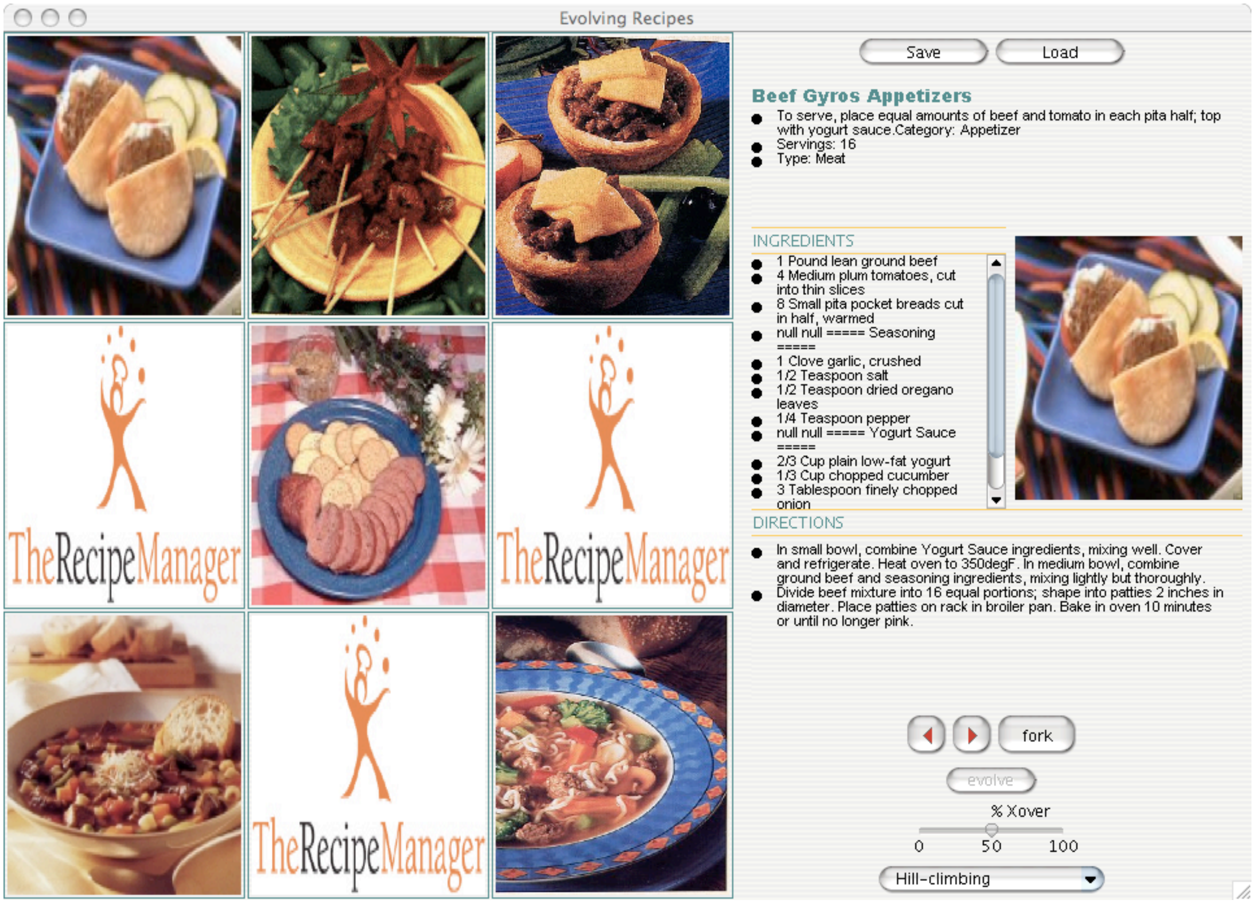

Figure 6. The next generation of search results.

Conclusions

Our Phase I project has been a great learning experience. Although we had not properly anticipated the need for external advisors in our original proposal, we took the reviewers' comments to heart and invested significant internal resources, in addition to NIAC's support, to reach out to the scientific, technological and space communities to assemble a team of advisors and to hold a workshop. We believe that we have made significant progress in understanding what steps need to be taken in order for this work to continue, and eventually to reach our objective of a food machine for space.

As a tangible outcome, we have developed a prototype tool that applies our IEC technique to the problem of searching for a recipe from a database. The prototype tool is limited in its power because of the relatively small database we were able to acquire. We hope in the future to team up with companies with much larger recipe databases, in which case our tool might become commercialized.

Our project has captured the imagination of many individuals and organizations. Almost everyone who heard of the project was fascinated by the idea of a food machine for the future. Our work received significant press coverage, including a cover story in *New Scientist*, and a mention in a cover story in *Fast Company*.

We hope to be able to continue this fascinating and stimulating (and appetizing) line of work.