Communal computing for 21st-century science

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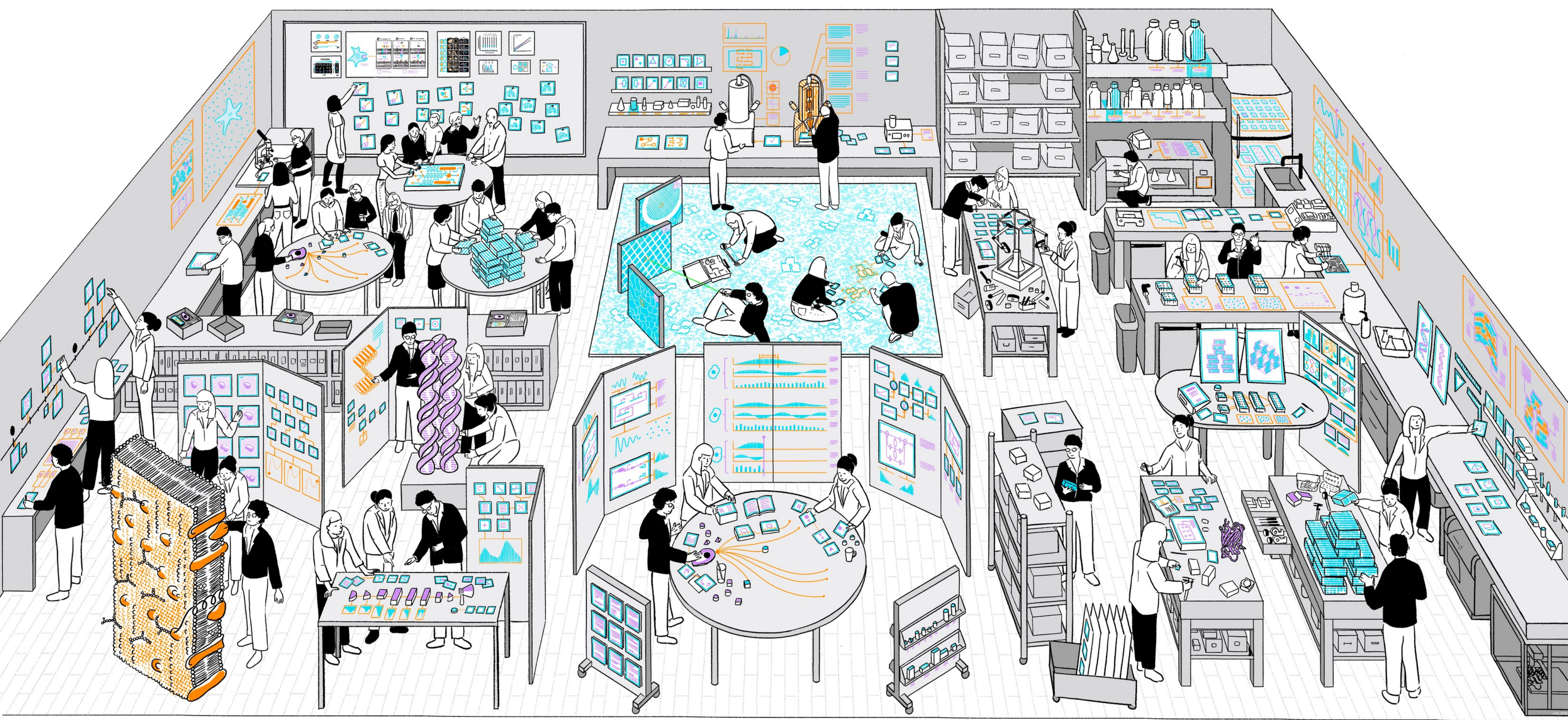
The greatest leaps in the progress of civilization have come from new forms for seeing and discussing ideas — written language, mathematical notation, interactive computing — which we might broadly call "user interfaces". Despite the abundance of computers in today's scientific process, we believe that scientists are not yet using the full power of computation to see and discuss their ideas. Scientific practice awaits its breakthrough user interface.

We are inventing *communal computing* as the user interface of 21st-century science. Computation is integrated into the physical world, and scientists see and discuss ideas by constructing immersive environments of dynamic models, in which invisible concepts are made visible and tangible.

A transformative interface cannot be invented in a vacuum, but must emerge within a thriving context of real cutting-edge practice. To establish this context, we intend to create a *molecular makerspace,* in which experts across many fields will converge to collaborate on nano-scale projects using novel tools and practices. The needs of this community will fuel the invention of a fundamentally new computing medium for doing science, and the community itself will carry 21st-century science into common use.

Long-term, we see communal computing as opening the door to universal scientific literacy. The graphical user interface created billions of computer users. We aim for billions of scientists.



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Introduction

A brief description of communal computing and the molecular makerspace.

- User interfaces give physical form to invisible concepts.
- Communal computing is the user interface of 21st-century science.
- The first 21st-century science lab will be a molecular makerspace.

Illustrated scenario

In which a hypothetical group of scientists collaborate at the molecular makerspace. This is just one scenario, and one configuration of the space, out of the countless projects, fields of expertise, and configurations we imagine moving through the space every day.

Prior work

While futuristic, nothing depicted here is science fiction. We have already developed many of the core technologies required, and the scenario extends from our real working prototypes. We do our day-to-day work within a communal computing environment like the one shown, and have developed communal computing communities.

Long-term vision

Someday, billions of people will create and discuss computational models of physical phenomena, and immerse in invisible systems that today only professional scientists have a true picture of. We believe that universal scientific literacy will prove critical for stewarding the planet toward a sustainable future.

People

Shawn Douglas co-invented 3D DNA origami, and created the CAD interface which made the field of DNA origami take off. Bret Victor and Luke Iannini co-invented Realtalk, the world's only self-hosted communal computing environment. Earlier, Victor was a user interface designer at Apple, involved in the design of the iPad and macOS.

User interfaces give physical form to invisible concepts

Nobody asked for the invention of the graphical user interface. It wasn't on any national research agenda. There was no demand from users — they were a small cadre of professionals using computing for specialized technical tasks, and accepted command-driven textual interfaces as simply what it meant to use a computer. There was no demand from the public — most people never expected to touch a computer in their lives.

The concepts around directly manipulating information arranged spatially on a screen were invented unbidden by a small group of visionaries, particularly in the research groups of Doug Engelbart and Alan Kay in the 1960s and 1970s. They believed that computing could be more than just number crunching, that it could serve as a medium for all people to see and discuss ideas, if only those ideas could be represented in visible, manipulable forms.

These concepts eventually became ubiquitous via the Apple Macintosh, Microsoft Windows, and World Wide Web. This was the breakthrough which enabled computing itself to become ubiquitous. The invention of this interface enabled every person on Earth to be a computer user, and enabled computing to be used for everything.

In a broad sense, we can define an "interface" as giving *physical form to invisible concepts*, thereby transforming the ways in which these concepts can be seen, reasoned about, manipulated, and discussed. The graphical user interface gave visible and spatial forms to computational concepts, precipitating a global transformation by people who could now apply their visual and spatial understandings to anything that could be represented computationally.

Some of the greatest leaps in the progress of civilization were driven by new "interfaces" in this sense. Going back a few millennia, we find the most transformative interface of all time: the invention of writing, and especially the alphabet, which physicalized *language*. Intangible, ephemeral sounds became physical marks that could be seen, studied, played with, and preserved.

In the 14th century: the invention of place-value Arabic numerals, the first "user interface for numbers" which enabled calculation to be done on paper. This made *arithmetic* visible and manipulable, and enabled universal arithmetic literacy.

In the 17th century: the invention of algebraic notation as a "user interface for mathematics", making *mathematical relationships* visible, manipulable, and abstractable in ways that recipe-like procedures never could.

In the 18th century: the invention of the data plot as a "user interface for data", enabling people to apply visual understanding to *changes over time*. All of these interfaces are taken for granted today, but without them, modern science would be literally unthinkable.

These weren't mere inventions or discoveries. Each of them made possible *all subsequent breakthroughs thereafter.* A fundamental new interface affects everything, forever.

More information

The Humane Representation of Thought (1 hour presentation)
dynamicland.org/links/2014-10-24

Communal computing is the user interface of 21st-century science

An interface gives *physical form to invisible concepts,* and in science, invisible and intangible concepts abound.

A researcher transfers liquid to a test tube, where invisible molecules undergo invisible reactions, forming invisible bonds according to invisible forces. She codes a Python script, setting up intangible algorithms to manipulate invisible data, to simulate an intangible model based on invisible mathematics. She presents her work to colleagues, attempting to represent invisible and subtle dynamic systems using words and cartoons.

Like computer specialists before the graphical user interface, today's scientific specialists are generally not asking for any change to this state of affairs. The challenges of wrangling the invisible are accepted as what it means to do modern science.

We envision a "21st-century science" in which all of these concepts are visible, tangible, manipulable things-in-the-world, and scientists employ the full range of human capabilities in working with and discussing them. If carried to full fruition, we can expect the effects of this interface to be no less transformative than the great interfaces of past centuries.

Computing

As we envision it, this transformation will require a radical reconception of what *computing* is, and how it is integrated into scientific life.

Today's scientists use computers, of course, and seemingly for everything — planning experiments; collecting, analyzing, and visualizing data; simulating mathematical models; communicating with collaborators; reading and writing papers; presenting slides. Computational power expands every year — yesterday's supercomputer is today's pocket watch — and every year, scientific computing seems more sophisticated and indispensable.

We believe that computing as it is used in science today will be seen in retrospect as shockingly limited, disconnected, and debilitating. Communal computing is founded upon fundamentally new technologies for *computing with anything, computing by everyone,* and *computing as communication.*

Computing with anything

In today's science lab, computing takes place on screens. A 21st-century lab has no need for screens, or even "computers" as such, because all physical space and all physical materials can be computed with. Everything from tiny test tubes, to cardboard boxes, to walls and floors are programmable objects.

Similar to how the 19th-century introduction of electric light transformed architecture and the nature of work, this space is illuminated with "21st-century light", enabling everyone to bring physical objects to life.

With this capability, scientists work with invisible concepts via *dynamic models* — computational models present in the real world. These models can have whatever physical form is best for understanding and manipulating them: sticky notes, sculptures, board games, wall murals, entire rooms. People hold them, hand them to each other, gather around them, walk within them, inspect them closely or notice them peripherally. Scientists develop deep intuitions for invisible concepts because living dynamic models are everywhere and used for everything.

Science is about what happens in the physical world. With computation also integrated into the physical world, models aren't restricted to the "possible realities" of simulations — they can represent the "real reality" on the lab bench at that very moment. An experimenter uses computation to see what her molecules are doing, and to make them do other things. *Molecules and computation live in the same world*.

These models are *multiplayer by default.* Because they are physical, everyone can see them and get their hands on them at all times. All activities become group activities, and invite spontaneous collaboration.

Perhaps unexpectedly, computing in the physical world has *drastically lower complexity and greater flexibility.* Computational activities make heavy use of physical and social mechanisms, so the parts that require actual computation can be relatively small and high-leverage. These properties are critical for achieving *computing by everyone.*

Computing by everyone

We envision all scientists expressing their ideas by crafting and programming dynamic models.

In today's lab, programming means typing code into invisible codebases. In a 21st-century lab, the program that implements a model is exactly as physical as the model itself. Like models, programs can have any physical form, from notations written on sticky notes to components arranged as wall murals, and are composed out in the real world where everyone can get their hands in. Different scientific fields use different notations and toolkits, which integrate seamlessly in real space.

In the same way that scientists develop intuition for molecules by being immersed in models, they develop computational fluency by being *immersed in programs.* Programs are everywhere, dynamically revealing their internal state for all to see at all times, and people are constantly tinkering with them, remixing them, discussing them, and building them together, out in the open.

The knowledge and assumptions behind a model are *not hidden,* and cannot be hidden, because its program is always right there. Everyone sees how it works, and everyone can try out alternatives. This is the core ethos of science, and it applies here not just to computational models, but to computational tools and even the computing infrastructure itself.

In today's lab, scientists depend on apps and operating systems — mass-distributed products from software developers. Even if open source, their internals are invisible, inflexible, forbiddingly complex, and not practically modifiable for most scientists. Using an app rarely leads to learning the knowledge that went into it. Instead, it acts as a trap, preventing the user from going beyond the app's assumptions.

Science is about the unknown and unsettled, where every problem is unique. Mass-produced tools are inappropriate. In a 21st-century lab, *learning a tool means learning how it works,* and immediately having the agency to modify it, remix it, or apply its knowledge elsewhere.

Toolkits evolve like any scientific practice, with scientists offering ideas and others freely adopting or adapting them. Every lab accumulates its own idiosyncratic set of physical computational tools. This includes the toolkits which implement the computing infrastructure itself. Every lab is its own "operating system".

Computing as communication

In today's lab, people talk to each other. In a 21st-century lab, people still talk to each other, but they do so while sketching dynamic models.

At the speed of thought, their vague intangible ideas become concrete scratch-paper programs, incorporating known facts and data, with implications immediately visible and explorable. They propose models, argue with models, refute models, refine models. The conversation spreads out, filling the space around them, immersing them within a shared imagination.

Because computation is everywhere, model-driven conversation can happen in the most relevant context — a wet lab, a machine shop, an instrument — where real-world materials and data that are lying around can be readily incorporated into the models.

* * *

Today, cross-disciplinary collaboration can often resemble outsourcing, where collaborators work separately, and combine their parts without learning each other's knowledge. We believe that breakthroughs require deep knowledge across many domains, and over-specialization yields stagnation.

In a 21st-century lab, every phase of the scientific process — designing experiments, carrying out experiments, analyzing data — is as inherently communal as a wood shop or kitchen. Collaborators work side-by-side on visible, tangible models, and gain each other's expertise. Even people on the periphery pick up on what's going on, and drop in to collaborate. Knowledge naturally spreads through everyone present.

* * *

Today, a presentation is a slideshow, and a publication is a paper. A 21st-century presentation is a guided tour through an immersive environment of dynamic models. The audience explores the models, examines the data firsthand, even reconstructs the models themselves. They try alternative scenarios, challenge assumptions, perhaps even make their own discoveries.

A publication is much the same, except a group of readers downloads the environment into their own computational space for a self-guided tour. Perhaps, when they come across a paper from today, they marvel that anyone could have ever grasped such intangible concepts by just reading words.

The first 21st-century science lab will be a molecular makerspace

Creating "another world"

21st-century science, as we've described it, is more than just technology. The way that people work, think, and communicate are all fundamentally changed. An interface is transformative because it transforms the *people.*

Such an interface cannot be invented in a vacuum. In a sense, it can't be "invented" at all — it must be *grown,* co-evolving along with a community of transformed people.

The graphical user interface was grown within the extremely unusual research labs around Doug Engelbart and Alan Kay, in which the laboratory itself was the experiment. The inhabitants of these labs were charged with reinventing the total context in which they themselves were working, evolving a system of cutting-edge tools and practices that were completely unlike anything outside. These communities effectively took themselves to "another world", and the new interfaces emerged over many years from the needs of their new world.

The best examples we know of, including those from our own Dynamicland, emerged from "other worlds" like these. Conversely, there have been many attempts to invent new interfaces within industry or pure research, disconnected from any active community of practice, and these have largely been sterile or stillborn. We need to do what actually works.

To create 21st-century science, we must create the "other world" where the culture and technology will co-evolve, and carefully design this context so the necessary characteristics emerge:

- We want to transform the practice of cutting-edge science, so this must be a place where real cutting-edge science is happening.
- We want something that applies generally across many fields, not a single speciality, so there must be a great *variety* of cutting-edge science.
- A primary focus is cross-disciplinary communication, so there must be many collaborators *integrating* their diverse knowledge and materials.
- We want the participation of established scientists who already have their own labs and practices, so there must be a way for them to *visit* our "other world" and get immediate benefits, but then return to their own world.
- To rapidly evolve the platform, there must be *rapid feedback cycles* of exploration, design, experiment, and analysis.

The molecular makerspace

Given these criteria, our first "other world" will be a *molecular makerspace.* Scientists across a wide range of fields will visit for short-term residencies, to collaborate with each other on cross-disciplinary projects.

At the molecular level, these collaborations will be enabled by one of the most promising molecular "integration technologies" — *DNA origami.* This is a technology for assembling completely custom nanostructures, using standard benchtop equipment, that can integrate precisely-placed ligands from across biology, chemistry, electronics, and more. Its simplicity and versatility make it a natural substrate for projects that bring together people from different fields.

At the computational level, these collaborations will be enabled by *Realtalk,* the next-generation computing system evolved at Dynamicland for communal computing with physical objects.

Collaborators will thus learn to use cutting-edge molecular technology to rapidly integrate their materials on the nanoscale, within a cutting-edge computational environment for rapidly integrating their ideas and knowledge on the human scale. We expect this proposition to be compelling to the kind of pioneers who are up for shaping 21st-century science.

Because visitors will initially be unfamiliar with both the molecular and computational tools and practices, these collaborations will be heavily facilitated by the lab's staff and the larger community.

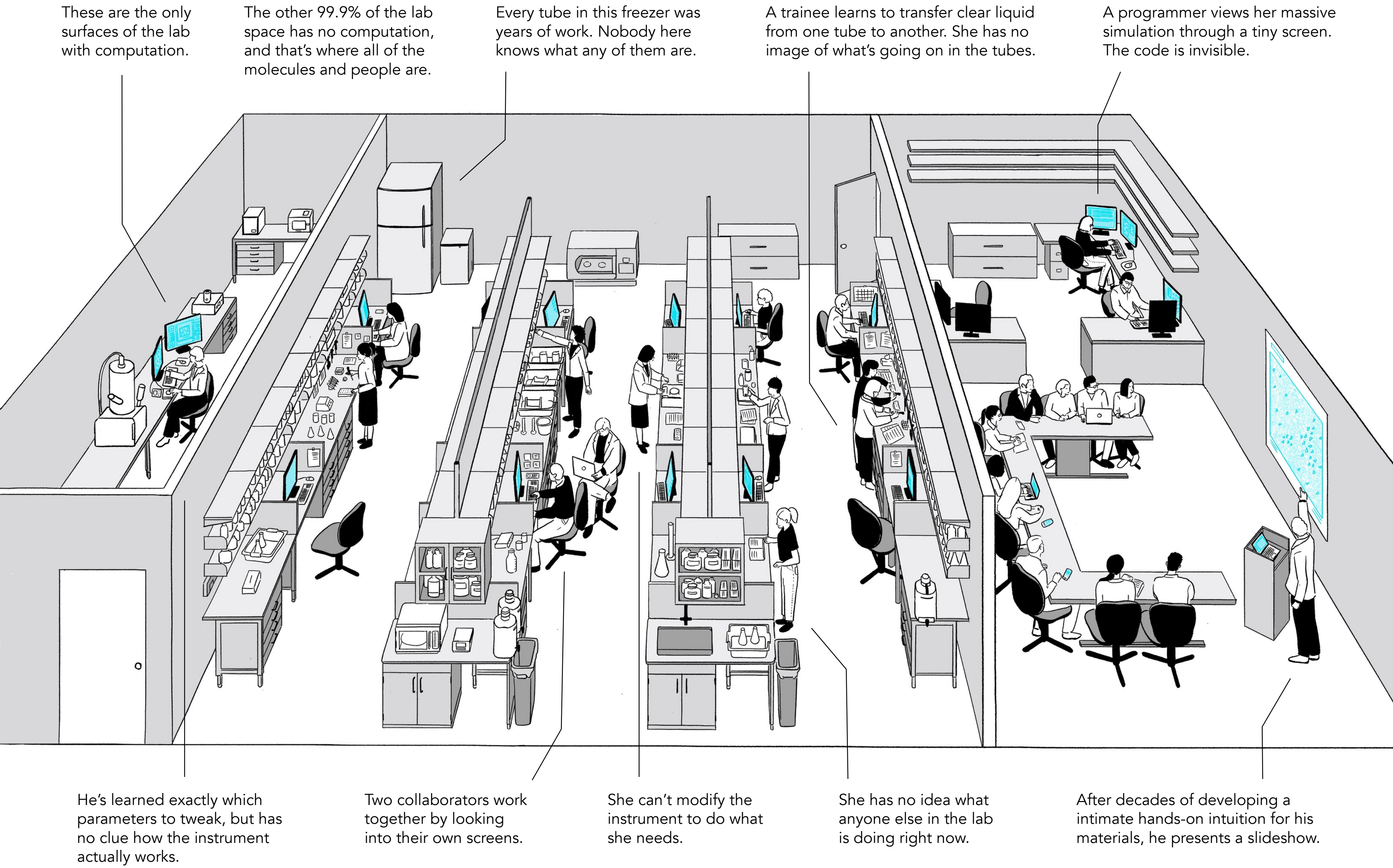
While we expect these collaborations to yield valuable results, their deeper purpose is to provide the context for evolving the platform. The primary research of the lab's staff will be at the meta level — continuously improving the computing environment, the molecular technology, and the cultural practices around them — to grow an ever more visible, tangible, 21st-century way of doing science.

Because a thriving community is critical for this project, the molecular makerspace will further serve as the worldwide molecular "community hub", hosting seminars, workshops, summer camps, and other events — all taking place within the communal computing environment.

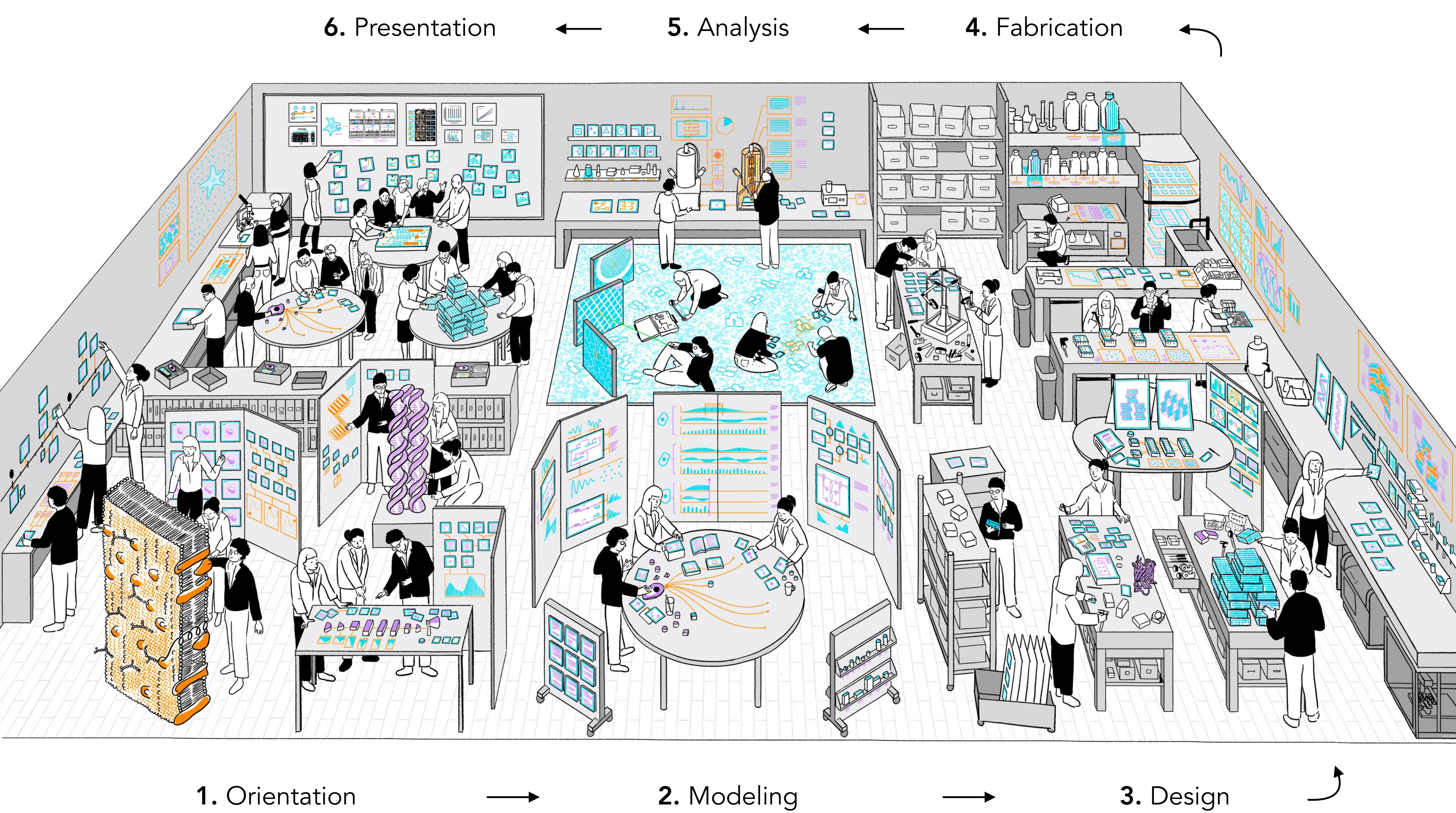
There will be a constant flux of visitors passing through and experiencing 21st-century scientific life. Some will stay to collaborate, a few will stay forever, and many will carry the ideas back home in some form. It will be this community which eventually brings 21st-century science into common practice.

Illustrated scenario

A standard science lab today



The molecular makerspace in five years



1. Orientation

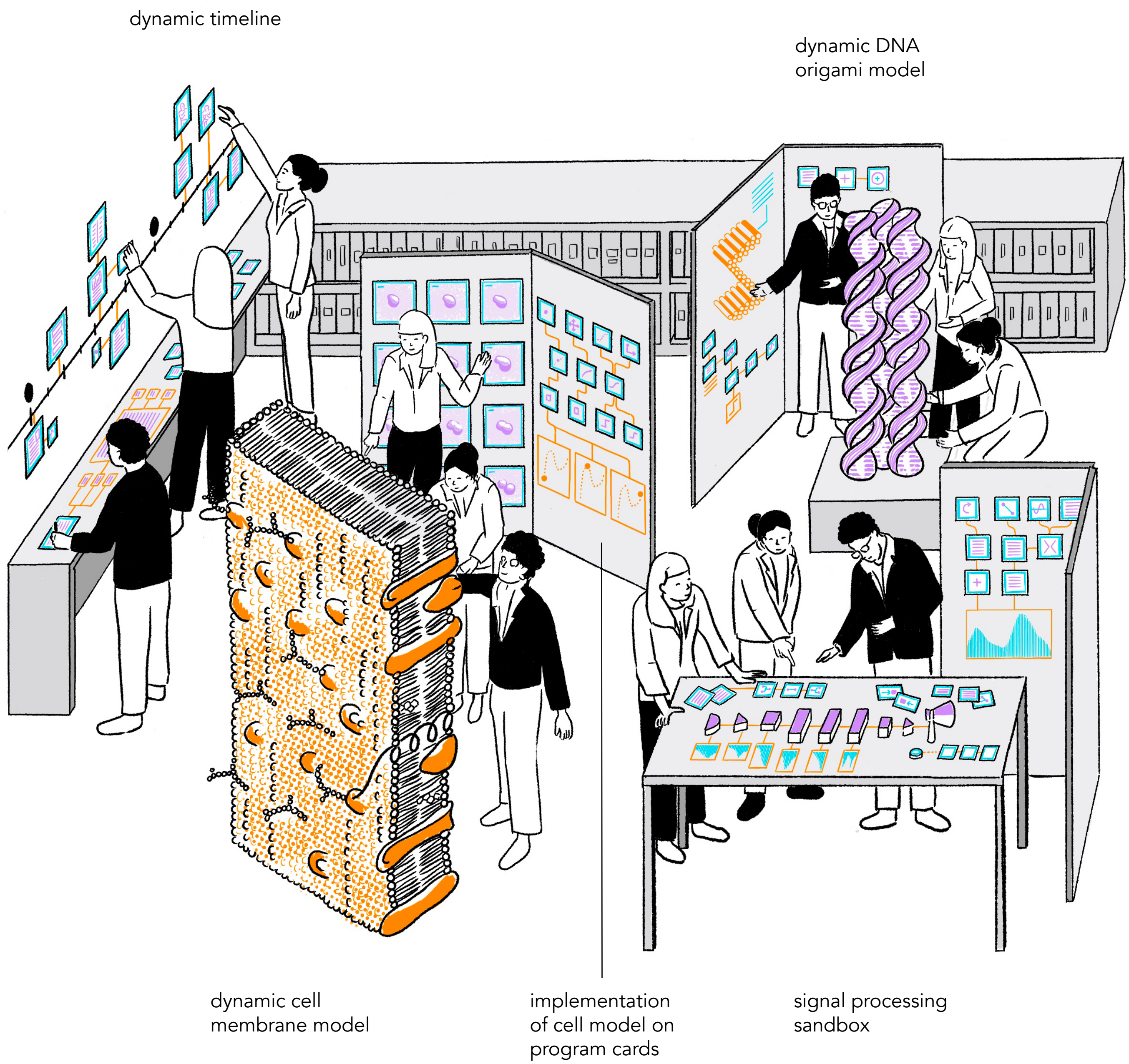
A cell biologist, electrical engineer, and nanoscientist have come to the makerspace to create a new kind of biochip for studying cell behavior. They're eager and excited by the potential of this collaboration, but also feel a bit lost. They barely know anything about each others' fields, and have no idea what the possibilities are.

To establish a shared context, they build a dynamic timeline of the history of their fields. As they tell stories, they handwrite the names of topics onto cards, and information spills out along the table — encyclopedia entries, images, videos, publications. They assemble these bits into a living mural along the wall, making notes, following connections, developing a common language.

With this shared history as a backdrop, the three researchers present the basics of their fields. Not with slideshows, but with tangible dynamic models that everyone gets their hands on.

They gather around a dynamic cell membrane, the biologist pointing out her favorite mechanisms in simulation. The engineer notices a signal pattern that might be detectable through autocorrelation, and demonstrates the technique by guiding the others through building a signal processing circuit. The nanoscientist thinks of a structure that could stimulate this signal, and shows off DNA's structural properties with models that come alive in everyone's hands. The researchers see that their fields have much to learn from each other, but also more in common than they realized.

Late into the night, the three researchers play with each others' models, finding connections, reprogramming them in conversation to simulate ideas that come up. In a space where cells and molecules are so viscerally real, anything seems possible. They finally hash out a plan for a biochip that none of them could have imagined before. They can't wait to get started.



2. Modeling

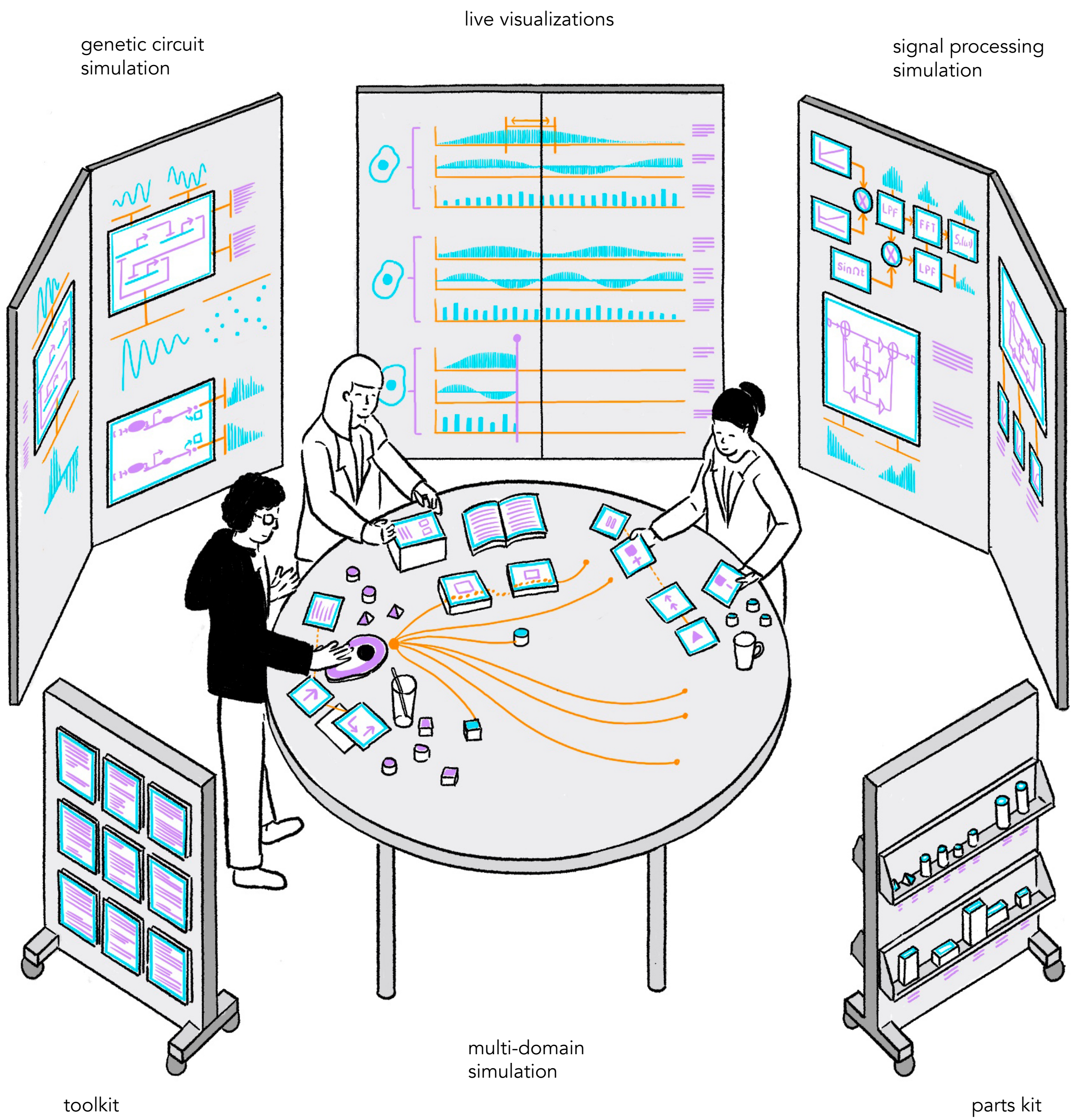
The three researchers have a plan, but it's a vague image in their heads, and further conversation reveals that they're each thinking of something different. To get in sync, they set up a space to build a whole-system simulation.

Dragging over domain-specific computational toolkits and arranging program cards on large posters, the biologist sketches the genetic circuit in her modified cell line, the engineer sketches electrical circuits for sensing and processing data, and so on. Because the simulated behavior of these circuits is immediately visible as it is drawn, everyone gets their hands in, tries out alternatives, and gets a feeling for how the circuits work.

These components are expressed in different notations and simulated by different programs, but they all come together on a central table, where a simulated cell interacts with a simulated biochip. Everyone cheers each time they bring a component to life and the prototype becomes progressively more realistic.

Intensely exploring their model, the researchers rewind and fast-forward simulations, reveal trajectories, overlay trajectories across ranges of parameters, and build up a clear picture of the space of possibilities.

Their models are crude, but the orders of magnitude are right, and soon it's obvious that their original idea would not have worked. Nobody is disappointed, though; they're elated that they caught their misconception now, before going through the long process of designing and testing a real device. Besides, there are so many better ideas that are now apparent. They choose a promising one, and get ready to design a chip.



3. Design

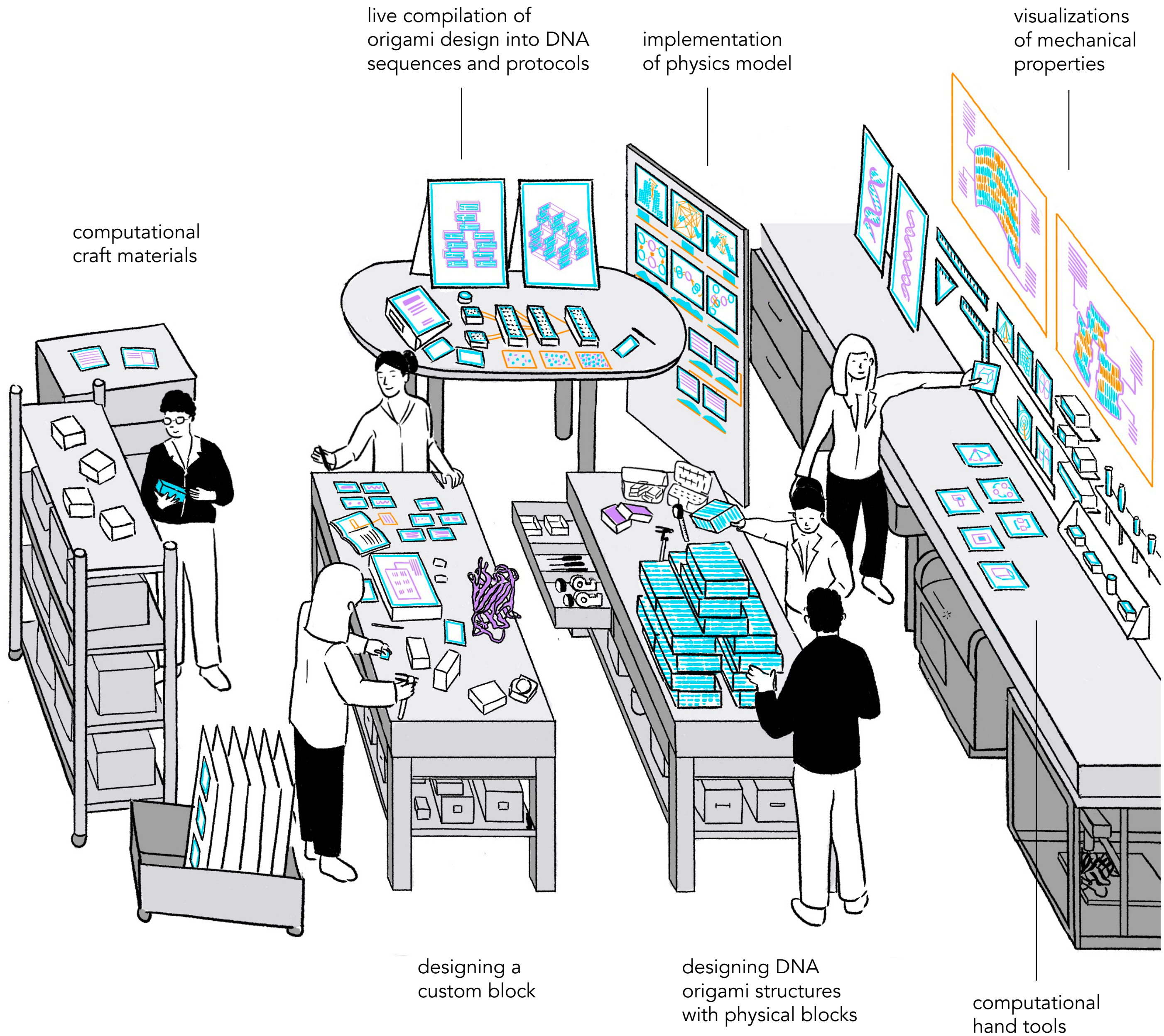
The three researchers start designing the DNA origami nanostructure for the substrate of their biochip. As they snap together blocks to construct a scale model, live simulations display their design's mechanical properties. The biologist and engineer have never worked with DNA before, but they find they're quickly developing an intuition from how the models react in their hands. The three of them chat and build together, the nanoscientist showing off his favorite motifs, the others excitedly pointing out their discoveries.

To probe and modify their designs in detail, they grab some computational hand tools from the tool wall. One tool is almost what they need; the biologist modifies its program by writing on it with a pen.

The engineer has some experience with particle simulations, but there's something unfamiliar about these. The physics model is running on a nearby poster, and the three of them take it apart. As they rearrange the forces, the engineer gets some ideas for the MEMS project she's been thinking about.

The biologist needs a new kind of block to bind her ligand. On another table, they arrange the program for the block, and play with the binding model. The entire kit of blocks was made, over time, at this table. On the shelf behind them are other kits, implementing other nano-architectures. The nanoscientist suggests a hybrid architecture, spilling a second kit onto the table.

As their designs come together, they keep an eye on the live-generated wet lab protocol, which incorporates the lab's current inventory and instrument availability. Soon it'll be time to fabricate.



4. Fabrication

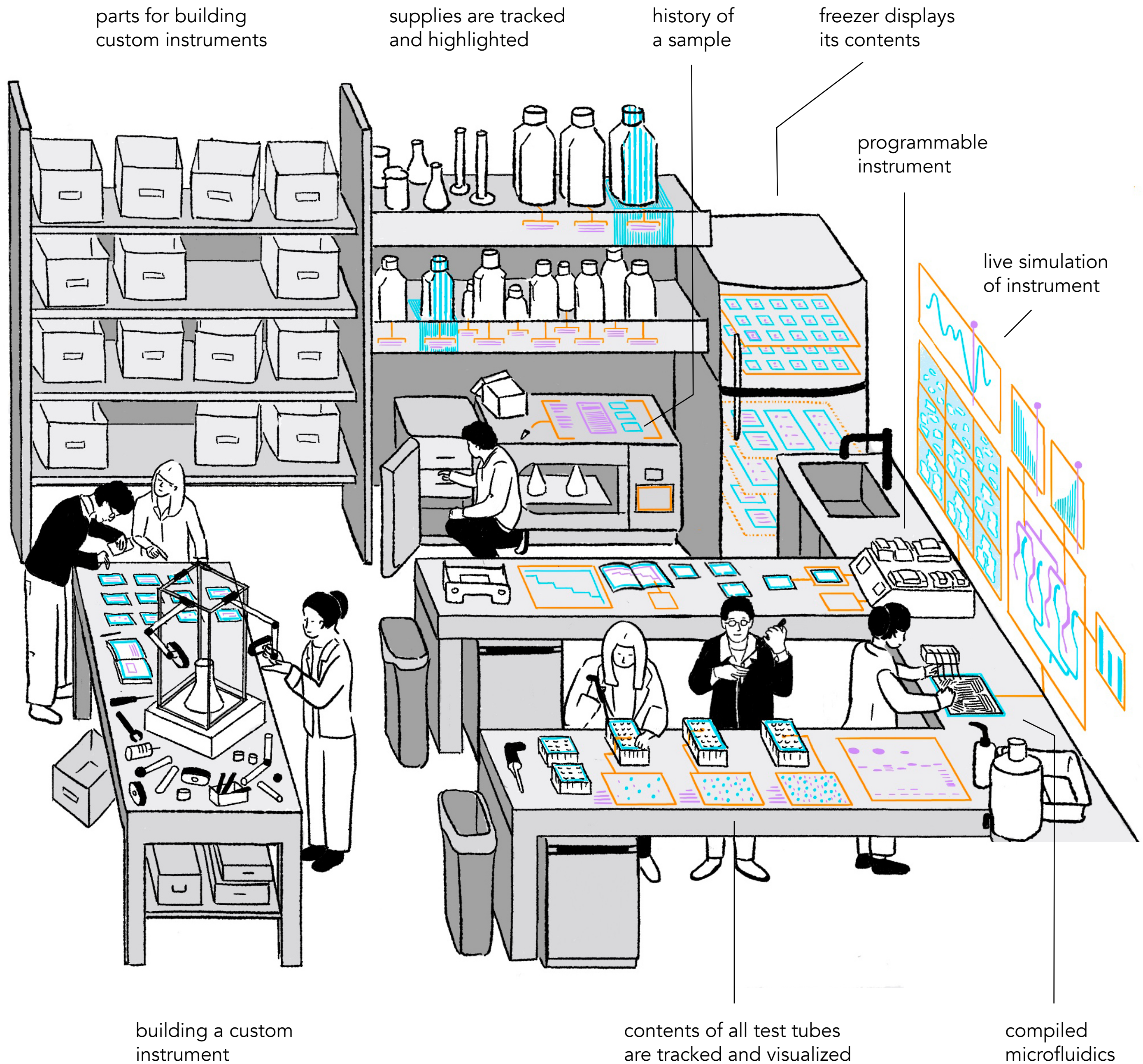
As the researchers carry their designs into the wet lab, the entire room lights up, configured for this protocol. A freezer beckons the engineer to take out a tube of scaffold DNA, and the tube fans out a history of how the sample was made and used. The engineer curiously flips through some of this sample's past experiments, noting some unusual uses.

As the researchers start pipetting together, the biologist remarks that it feels like baking with friends. Above every test tube is a live visualization of the molecules within; every reagent and every reaction is plainly visible. Before, molecules had always felt like vague abstractions. Here, as the researchers move liquids around, they have the uncanny feeling that they're touching the molecules themselves.

Another uncanny feeling is that of programming the molecules themselves. The nanoscientist suggests trying a range of variants, and together they arrange a program which compiles into 3D-printed microfluidics. Watching the live visualization as their device runs, the engineer spots a mistake which they patch up by hand. Meanwhile, their protocol program has noticed the deviation, and has updated the room accordingly.

The engineer draws a temperature ramp in the lab notebook, and watches the live simulation as the thermal cycler runs. The simulation is based on the latest model of how DNA origami folds, but lately the nanoscientist has noticed results that don't match the model. He's stored the anomalous data on sticky notes above the thermal cycler, and the model's author is coming over later to discuss.

Meanwhile, the biologist wants to do an optical density measurement for which no instrument is available. The researchers pull a few boxes of mechanical parts and sensors off the shelf, arrange a program on the table, and improvise an impromptu apparatus. With the same computational tools that they used to build models, they've built a real device.



5. Analysis

Like all instruments, the microscope is integrated into the computational environment of the room, and many people have enjoyed building their own physical interfaces to it. Trying a house favorite, the researchers configure the microscope's parameters by physically adjusting a scale model, while visualizations reveal the behavior of the electron beam. The engineer has used SEMs before; they felt like complicated and mysterious black boxes. But here, by simply configuring the microscope, she learns how it works, top to bottom. This microscope has seen a lot of unusual uses and custom modifications over the years by people emboldened by this familiarity.

The researchers pin up their preliminary screening program, and the microscope starts scanning. Because this program was generated from their design, it knows what to look for, and automatically seeks out regions of interest to capture in higher detail.

The floor lights up, and the researchers are plunged into the nanoscale. They've built models and studied simulations, but nothing has prepared them for the thrill of literally standing among real molecules, relating to them at the scale of their own bodies. Holding interactive maps in their hands and navigating via powers-of-ten posters, the researchers romp within the micrograph, calling out to each other as they make discoveries, dropping markers at critical finds.

Using a nano tape measure, the nanoscientist examines the sizes and distances of their particles. The biologist and engineer set up camp around a cluster of particles, using cards on the floor to build a recognizer program. All of the recognizers collectively steer the microscope's search path, and the map lights up as particles are found and captured in high resolution.

The researchers build their analysis programs on the floor, lying among the data they're analyzing, overlaying visualizations. Their molecules become intimate companions. In coming days, the researchers find themselves going to lunch within the microscope, and even inviting friends over in the evenings to relax and explore the nanoworld.

6. Presentation

After many iterations of modeling, designing, fabricating, and analyzing biochips, the researchers discover a cell behavior which suggests a novel cancer treatment. Eager for colleagues to build on their breakthrough, they organize a workshop.

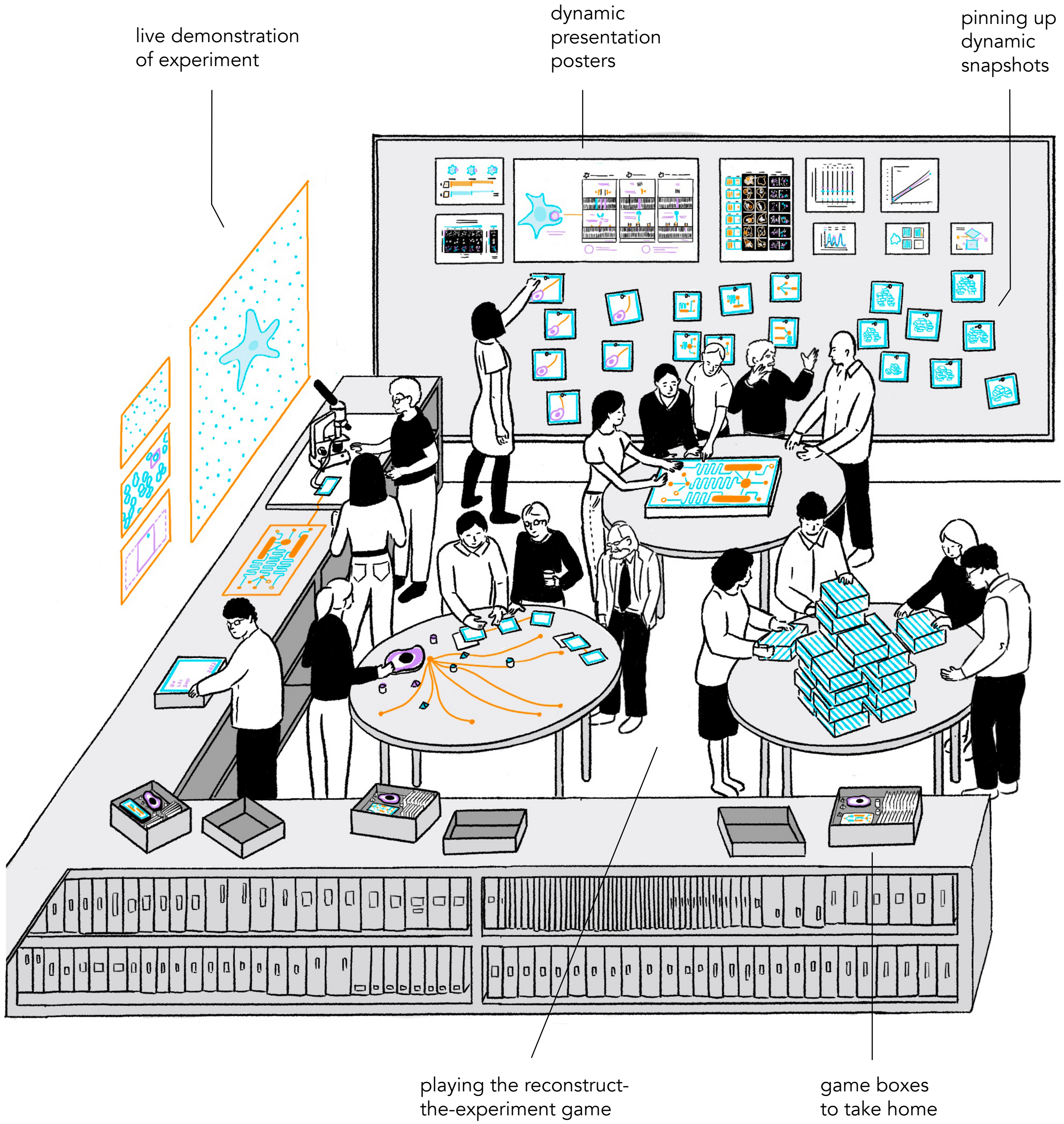
It begins with a walking tour through their dynamic models, showing and telling, recounting stories, immersing the audience in data and evidence, getting them excited about the discovery. But it's not enough for the audience to just appreciate the work. They have to understand it deeply enough to continue it. So after the initial tour, the real fun begins.

The audience divides into groups, and each group unpacks their game box. Inside are the pieces and tools that they'll need to construct their own model biochip. The biologist, engineer, and nanoscientist each lead one of the groups — by now, they're all familiar enough with each other's fields that they're comfortable guiding the entire activity.

As the groups play through the dynamic "board game", they recapitulate the research project in simulation — constructing the cell circuit, the DNA origami, the signal processing network; analyzing and iterating; facing and solving the same challenges. They don't understand every detail, but as they work with the dynamic models, a wordless intuition grows in their hands. The game reaches its climax and the groups feel exhilarated, like they've gained years of experience in just a few hours.

Now it's time for free play. Everyone here is an expert on something, and tears into their models from their own perspective, exploring new ideas with their new friends. As they come up with compelling variants, they pin dynamic snapshots on the wall and excitedly show them off to everyone else. Some participants have even brought their own cells, which they try out on the real biochip. In the chaos, dozens of promising collaborations ignite throughout the space.

Everyone heads home with a game box under their arm. Later, back at his own lab, a participant gathers his colleagues and unpacks the box. As they start to play, one of them says, "That gives me an idea for a project..."




Ceiling-mounted hardware...


... recognizes and illuminates physical objects.


Communal authoring


Learning through immersion


Dynamic tool wall


Exploring projects in the gallery


Integrating with electronics


Realtalk OS implementation

Prior work: Realtalk

An operating system for communal computing

Realtalk is the real-life basis for the computing environment described in this scenario, created by the Dynamicland Foundation and community over the last decade. Most of the computational capabilities in the scenario are already present in Realtalk, or are plausibly achievable within a few years.

In Realtalk, cameras in the ceiling recognize ordinary physical objects — index cards, books, board game pieces, 3D-printed models — and projectors illuminate them with visualizations. In this way, the entire building becomes the computer. Groups of people work together in real space, with everyone getting their hands on tangible computational objects on the table, while immersed in data on the walls.

Computational activities and tools are created by the users themselves. Programs are themselves physical objects, and thereby support a variety of authoring styles, from writing code, to spatially arranging objects, to drawing domain-specific hand-written notations. People learn to program by immersion — programs are everywhere, and everyone works on programs out in the open, where others can observe and join in.

Computational objects communicate by publishing readable information into the space — *"I am on lab bench 3"*, *"I am pointing at a map"* — which any other object can notice and react to. The simplicity and visibility of this model makes it possible for people to understand what is happening, and to take anything apart to extend it. Even the operating system itself is a compact and accessible set of physical objects, which can be live-edited by anyone at any time.

At Dynamicland, thousands of people used Realtalk to build hundreds of projects, covering topics from statistics to digital synthesis to poetry. Realtalk's networking capabilities allow projects to be physically carried between sites, or replicated remotely via the internet, laying the groundwork for a growing network of communal computing around the world.

More information

Dynamicland (45 min presentation)
dynamicland.org/links/2018-02-24

Progress report 2014-2019 (8 pages)
dynamicland.org/links/2019-09-09

Prior work: Biotech prototypes

Realtalk in the science lab

In 2022, we installed Realtalk in the Douglas Lab and began prototyping a biomolecular design environment that combines physicality, social interaction, live computational models, and pervasive programmability. Although we only created a handful of tools, they offered a tantalizing glimpse of scientific collaboration and discovery enabled by communal computing.

By leveraging physical models augmented with real-time simulations, we could design and manipulate molecular complexes easily and intuitively. Computational models provided immediate feedback during the design process, facilitating consistent shared mental models and catalyzing lively and fruitful discussions. Even visitors with no prior experience could quickly understand and generate new DNA and protein constructs in minutes.

The transformative potential of "computing with anything" became evident as we brought the wet lab to life with computational light. Our models, simulations, and design tools had no barriers to the lab's scientific tools, reagents, or instruments. We built a turn-by-turn navigation system for carrying out protocols. Benchtop instructions prompted the experimenter to gather the necessary plates, racks, tubes, and reagents, and suggested how to arrange them. Projected lines showed precisely what to pipette, where, and how much at each step. Using a laser pointer, we could point at any instruction or object to identify reagents, display information about them, and indicate their physical locations in the lab and where to order more.

The entire implementation of the prototype toolset was physically present as a small collection of posters, which could be examined and live-edited at any time. We contrasted this with our widely-used open source tool Cadnano, whose code has almost never been examined or modified by its users.

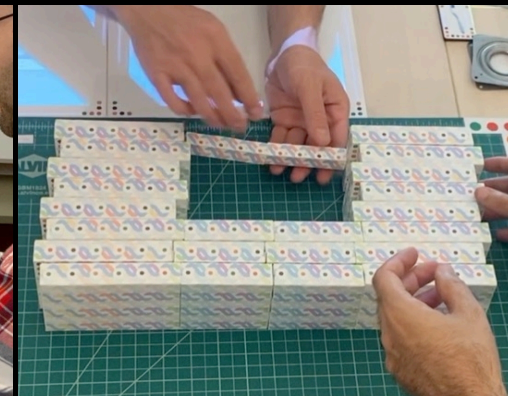
Our molecular makerspace scenario builds directly on what we learned from this prototyping experience.

More information

Biomolecular design in Realtalk (10 min)
dynamicland.org/links/2022-07-10

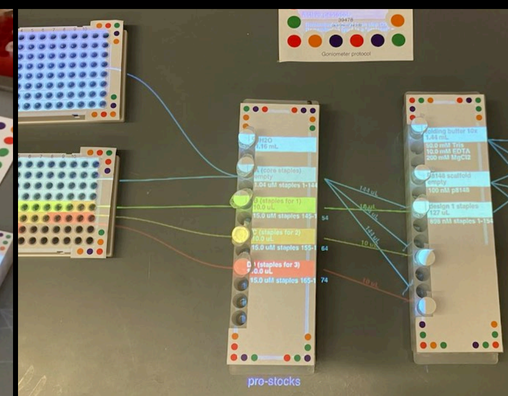
Nanoscale Instruments for Visualizing Small Proteins (30 min)
dynamicland.org/links/2022-10-29

Designing proteins together on the table.

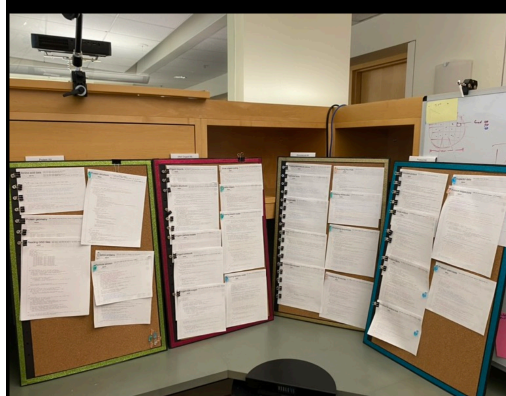


Designing a DNA nanostructure using physical blocks.

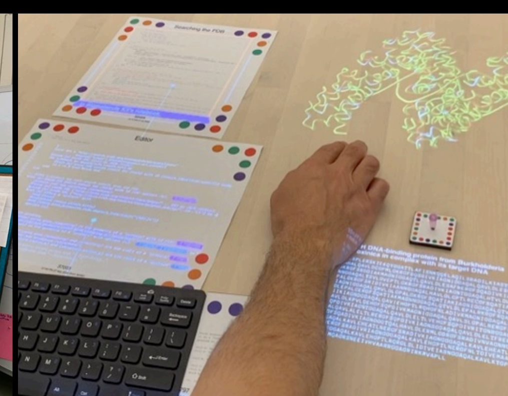
Pipetting with turn-by-turn navigation.



Test tubes show what's inside them.



Implementation of the full set of tools in 20 physical pages.



Tools programmed together on the table among the proteins and test tubes.


Community events


Model-driven discussions


Dynamic presentations


Human-scale dynamic models


Communal authoring


Dynamic “board game” books


Multi-week residencies


Exploratory workshops

Prior work: Dynamicland

A community-driven communal computing lab

We founded the Dynamicland community space in downtown Oakland, California, to establish our vision of communal computing in direct collaboration with a community of practice. With walls and tables illuminated by Realtalk’s computational light, hundreds of people could simultaneously work together to create and explore tangible dynamic models. Between 2017 and 2020, we hosted and taught thousands of visitors, from public community events to multi-week residencies to intensive workshops to class field trips.

We assembled the Dynamicland core community from dozens of local artists, engineers, educators, and community organizers who learned Realtalk from us, taught one another, and filled the space with a library of tangible models of topics they were passionate about.

Dynamicland was designed to give the community total agency within the system. A tool wall collected useful apparatus for manipulating and editing dynamic models, and community members came to know these tools as intimately as carpenters in a wood shop. A tutorial gallery held dynamic books teaching different aspects of the system — graphics, sound, spatial relationships — and it was an everyday occurrence for community members to modify the operating system itself, which lived on a set of illuminated whiteboards. In a dynamic theater, presentations took place with dynamic timelines spanning the room, and audience members physically placing living programs directly into the presentation.

On a given day, you might find a community member building a prismatic light simulation on one table, while a group nearby explored the harmonic relationships between different scales of music. A dynamic graph of social and economic data was connected to a dynamic map, which connected to a live satellite feed tracking wildfire progression and predicting air quality. Community creations and connections such as these happened constantly. We expect the molecular makerspace community to feel very similar to this.

More information

Bootstrapping Research & Dynamicland (30 min)
dynamicland.org/links/2019-12-12

Dynamicland narrative of activities (5 pages)
dynamicland.org/links/2020-05-29

Prior work: BIOMOD

A student biomolecular design community

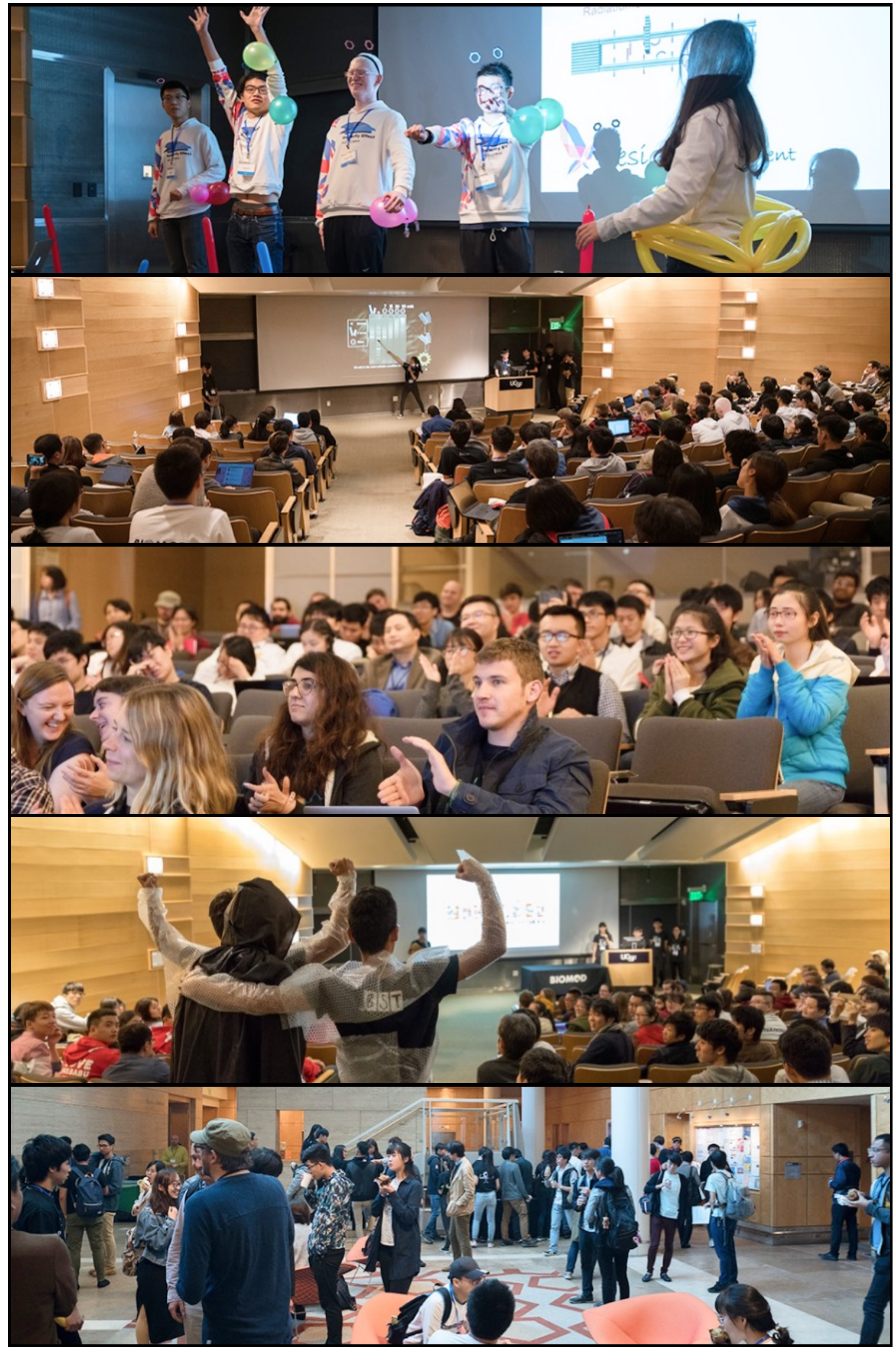
Dr. Douglas founded and organized BIOMOD, a global design competition to provide new opportunities for college-age students to gain hands-on experience in cutting-edge nanotechnology research.

BIOMOD is similar in format to the International Genetically Engineered Machines (iGEM) competition, which served as its inspiration. However, BIOMOD encourages students to explore the world of biomolecular nanotechnology.

Undergraduate participants team up with a faculty mentor at their home institution and learn to program DNA, RNA, and proteins to self-assemble into nanomachines and devices. Students must design, plan, and execute projects during the summer, and then travel to the annual Jamboree in the fall to present their work. A panel of faculty judges scores each project and provides feedback. The top-scoring teams win awards and prizes.

Since 2011, over 1600 undergraduate students, graduate students, and faculty mentors from 15 different countries have participated.

In 2015, Dr. Douglas incorporated BIOMOD Foundation, an independent 501(c)3 public benefit corporation in California, and currently serves as chairman of the board of directors. Dr. Douglas has raised over $300,000 in corporate sponsorship and federal grants to support student travel, lodging, and meal costs to host the event.



More information

BIOMOD
biomod.net

Long-term vision

In 1969, the first two nodes of the nascent ARPANET came online. By 1985, ARPANET had become the Internet, with 2000 nodes spanning from small desktop machines to the NSFnet's supercomputers. By 1999, the Internet spanned across the entire planet, with hundreds of millions of nodes, touching every aspect of human life.

In 2029, the second dynamic laboratory will come online, forming the first two nodes in a new *network of dynamic knowledge.* This second site will carry the culture of the first lab, by inheriting some of the dozens of researchers now fully fluent in the dynamic medium, and will be seeded with the thousands of dynamic models accumulating in the library of the first site.

This growing network of institutions, and the changes they bring in humanity's relationship to knowledge, will be the enduring achievement of our project. The practices in this proposal will spread first to peer laboratories, then to universities, and over the next decades, into most fields of human endeavor, just as writing and the internet before it.

Of particular importance is the diffusion of these practices into the public. Through sites like community health centers, schools, and public libraries, the public will learn new ways of interacting with knowledge, and with each other — the first steps towards our goal of *universal scientific agency.*

Visions from a dynamic future

In the future, a doctor may help a patient understand the changes occurring in their heart with the aid of dynamic models. With a tangible model of the patient's heart, they squeeze a particular artery to show how constriction of this passage causes this muscle to receive inadequate oxygen, and how that leads to this signal on the patient's EKG, as compared with a normal sinus rhythm. They show the patient how an arterial stent will relieve this constriction, and then carry the model with the patient's real data to the Cath Lab to discuss a strategy for ideal placement of the stent with the surgeon.

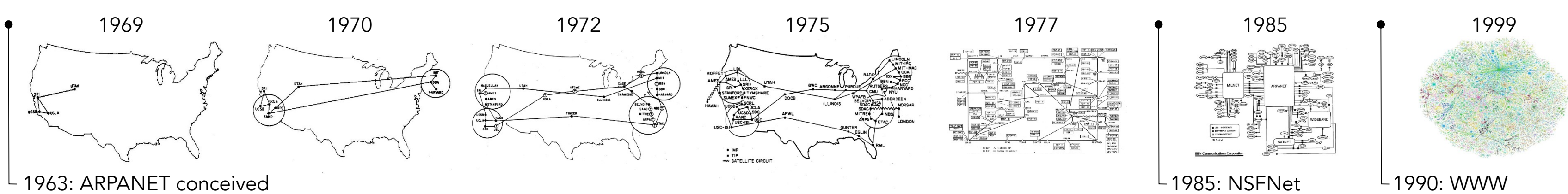
At a nearby public library, a community has gathered to understand a local nutritional health deficit. Through discussion they trace the root cause to a shortage of fresh produce caused by surrounding drought conditions. Adapting an agricultural model from a neighboring town, they rapidly fabricate topological maps of their community to find the best locations for of a series of community gardens, choosing a mix of local plants from a dynamic card catalog to provide the needed nutrients, and determining square footage based on the caloric needs of the residents.

When the simulation shows the water usage of these gardens may add too much load to an already-strained municipal water system, a dynamic book on rainwater harvesting systems shows possible solutions — they determine the needed water collection surface area needs and cistern volumes while scrubbing through historical rain patterns in their region overlaid on their neighborhood, and add them to their model.

A local soil chemist present at the gathering teaches soil analysis, and after a refresher on plant biochemistry, they design an ideal mix of plants to restore soil nitrogen levels for optimal growth. They realize no one has documented this particular planting pattern in their USDA growing zone, and contribute the design back to the library for others facing similar conditions to use.

In the coming decades, our relationship with health, technology, ecology and society must be radically rebuilt — new forms of ecological knowledge, technology and infrastructure must be invented, adapted to their local environment, manufactured from abundant materials, and managed by the communities they serve. To realize this, humanity's hard-won knowledge of the past centuries— chemistry, biology, physics, mathematics, electronics, simulation, ecology, sociology, systems — must be made accessible not only for universal literacy, but for universal agency. Building on the interdisciplinary insights of a vast and diverse body of dynamic human knowledge, billions of scientists will collaborate to build a world that is not only sustainable, but flourishing.

ARPANET to Internet, 1969-1999



Bret Victor

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Bret Victor led the team that invented Realtalk and founded Dynamicland.

Previously at Apple, he designed the initial user interface concepts for the iPad and several other new hardware platforms. His work established Apple's internal future-interfaces prototyping group, whose inventions have shipped in billions of Apple products.

His later public-domain work on next-generation programming interfaces has been viewed millions of times, and directly inspired numerous products, companies, and academic papers.

His work has won the Apple Design Award twice. Computing pioneer Alan Kay has called him "one of the greatest user interface design minds in the world today", and design legend Edward Tufte recognized him as a "design theory wizard, at the cutting edge of interface designs for programming, seeing, reasoning".

He has electrical engineering degrees from Caltech and UC Berkeley.

Luke Iannini

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Luke Iannini is a technologist with a long track record in interface design, digital signal processing, and augmented reality. He has been working with the Dynamicland team since 2016, when he co-created La Tabla, a tangible computing platform and precursor to Realtalk.

Previously, he was the founder and CEO of Hello Chair, Inc., pioneering early deep-learning techniques to power app discovery in Apple's App Store, techniques which became ubiquitous a decade later. In 2014, he founded Tree Computer, Inc, and worked as CEO and Chief Engineer to develop open-source virtual reality tools for Oculus and Valve Software's prototype systems.

He has found innovative ways to combine hardware and software to create novel and expressive user interfaces. He created some of the earliest multi-touch music composition software for the Apple iPad, and built immersive exhibits at the San Francisco Children's Creativity Museum. His work has been featured in the New Scientist and the Wall Street Journal.

Shawn Douglas

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Dr. Shawn Douglas is an Associate Professor in the Department of Cellular and Molecular Pharmacology at the University of California, San Francisco. He earned his Bachelor's degree in Computer Science at Yale in 2003 and received a Ph.D. in Biophysics at Harvard in 2009.

Working with Prof. William Shih, he pioneered methods to design and fabricate three-dimensional DNA origami nanostructures. He created Cadnano, a graphical CAD tool that is widely accepted as the standard platform for DNA origami design. In 2011, he founded BIOMOD, a nanoscale design competition for undergraduate students that has now hosted over 1600 participants from 15 countries.

Dr. Douglas's work has been recognized by the Burroughs Wellcome Fund (Career Award at the Scientific Interface), NSF (CAREER Award), Pew Charitable Trusts (Pew-Stewart Scholars for Cancer Research), Popular Science Magazine (Brilliant 10 Award). In 2017, he received a Presidential Early Career Award for Scientists and Engineers (PECASE), the highest honor bestowed by the U.S. government on outstanding scientists and engineers beginning their independent careers.

Illustrations by **Joanne Cheung**

April 2023

dynamicland.org/links/2023-04-27