

The communal science lab

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Dynamicland Foundation

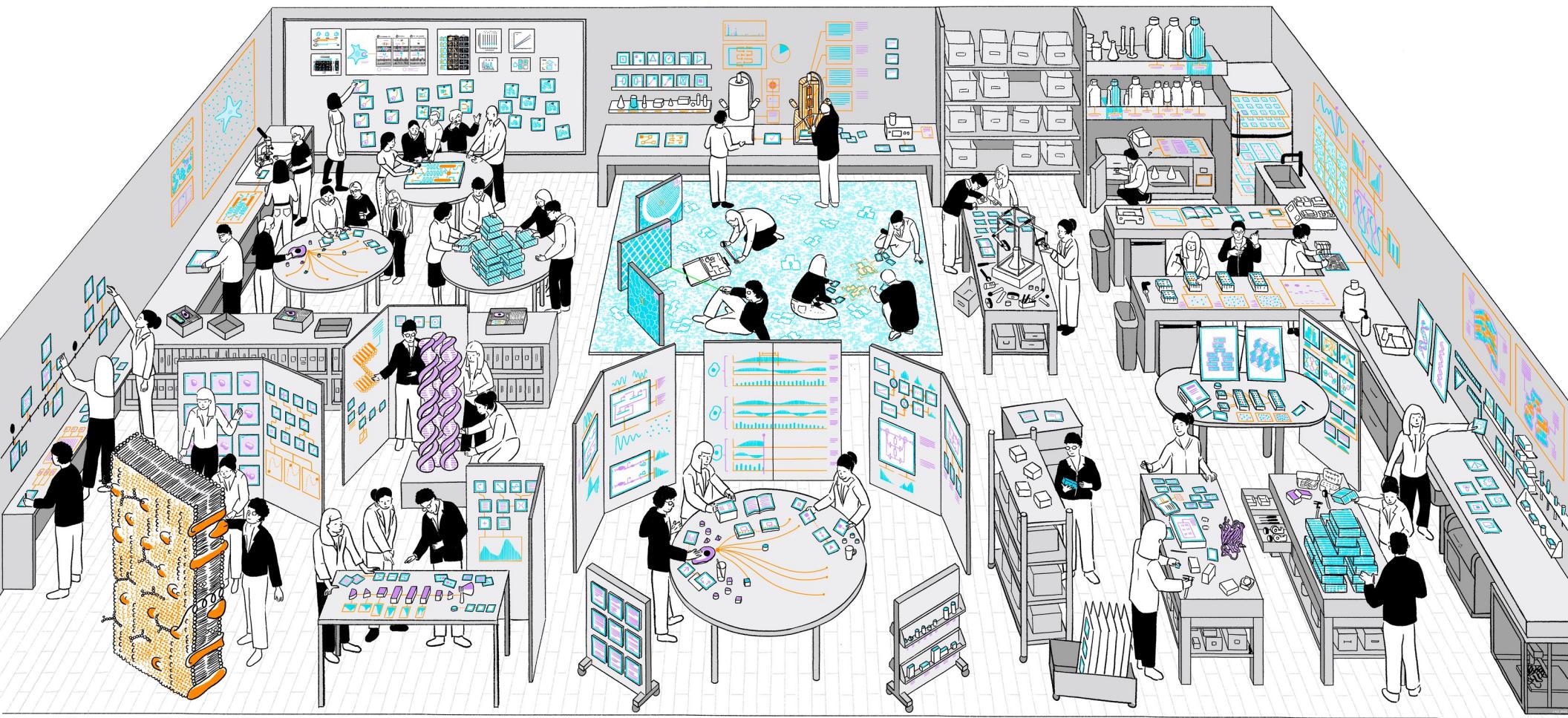
Shawn Douglas

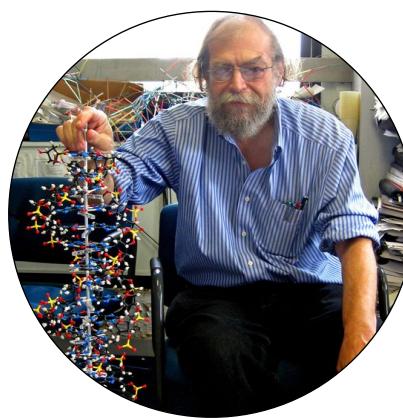
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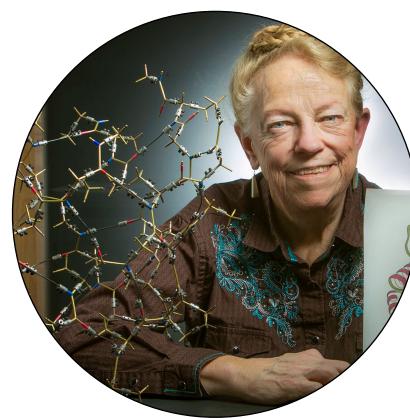
Despite the prevalence of computational technology in every aspect of the scientific process, today's computers are barriers to in-depth in-person collaborative work, preventing scientists from building and exploring computational models side-by-side with collaborators, learning from and extending their tools, and seeing systems and data in their entirety.

In our vision of *communal 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. Long-term, we see communal science as opening the door to universal scientific literacy.





Ned Seeman, founder of DNA nanotechnology, with physical model.



Jane Richardson, protein structure pioneer, with physical model.



Scientific work today is almost completely mediated by computational technology. Scientists use computational tools to design and simulate models, to plan experiments, to collect, analyze, and visualize data, to read and write papers, to give presentations at meetings and conferences, and to collaborate with colleagues both local and remote.

We believe that computing as it is used in science today will be seen, in retrospect, as shockingly debilitating. The computer in its current form will be seen as *disconnecting* scientists from their models and data, from the physical world that they're studying, and from each other. The computer will be considered a barrier to deep collaboration and deep understanding.

From this perspective, the most striking features of today's computers will be their complete disregard for four essential values:

visibility

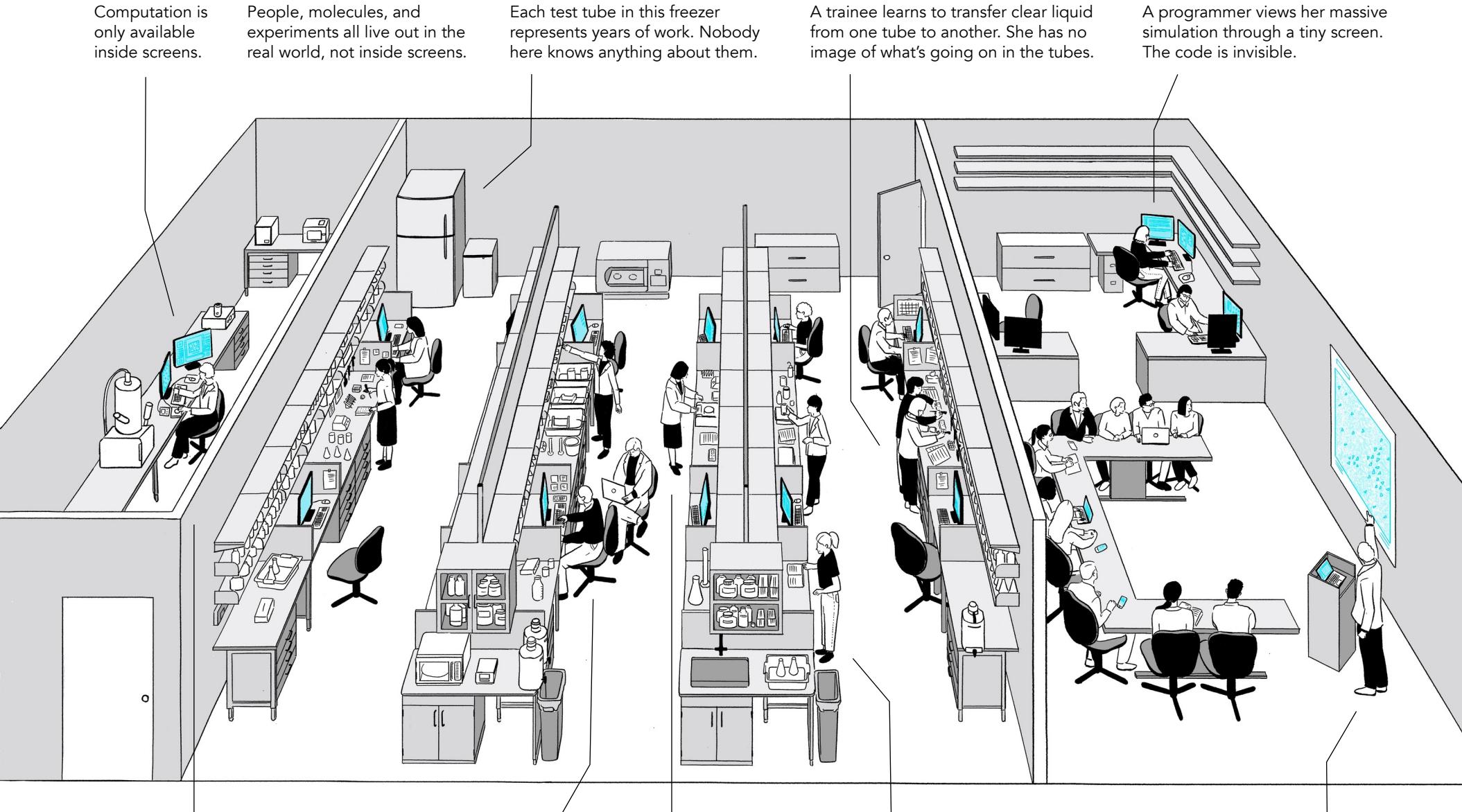
agency

physical reality

in-person collaboration

The situations on the following pages are ubiquitous throughout today's science labs, but are generally taken for granted rather than recognized as problems to be solved.

The standard science lab



Computation is only available inside screens.

People, molecules, and experiments all live out in the real world, not inside screens.

Each test tube in this freezer represents years of work. Nobody here knows anything about them.

A trainee learns to transfer clear liquid from one tube to another. She has no image of what's going on in the tubes.

A programmer views her massive simulation through a tiny screen. The code is invisible.

He's learned exactly which parameters to tweak, but has no clue how the instrument actually works.

Two collaborators work together by looking into their own screens, not at each other.

She can't modify the instrument to do what she needs.

She has no idea what anyone else in the lab is doing right now.

After decades of developing a intimate hands-on intuition for his materials, he presents a slideshow.

Visibility

A researcher creates a scientific model in Python. She sees sixty lines of code on the screen. The other thousand lines, and their overall structure, are invisible to her and to everyone else. Behind those, a hundred million invisible lines in libraries, apps, and operating systems. No single person has ever seen them all. Her code's behavior as it runs is invisible, and she must imagine what it's doing. The results of a run are either an unreadable text dump, or a visualization that condenses her massive simulation into the space of a tiny screen, with details and alternatives invisible.

She goes to the wet lab and transfers clear liquid from one test tube to another. The contents of the tubes are invisible, and like her code, she has to imagine the reactions within. She fetches a reagent from the freezer. The freezer is a repository of the lab's last decade of work, but the projects behind each of the tubes are invisible, and she has no access to this wealth of knowledge. Simply walking around the lab, she sees a dozen researchers typing into screens. What they are working on is invisible to her, and to everyone else. In this thoroughly computerized lab, almost nothing can be *seen*, both for the researchers themselves and for potential collaborators, supporters, and trainees.

Agency

A researcher uses a computer program to design a nanostructure, but the features provided by the app developer don't fit the unique needs of the researcher. The tool is nominally open source, but the source is a hundred thousand lines of forbiddingly-complex code whose structure and behavior are invisible. The only practical way to change the app is to ask the original developer to do it. The developer is a scientist who has moved on to other projects, and anyway, the dependencies are broken. Learning to *use* the app did not prepare the researcher to *change* the app; these are two different worlds. Nor did learning to use the app teach the researcher the scientific knowledge that the app is based on; she'd be better off reading the published paper than the code.

She goes to the wet lab and uses an instrument — an electron microscope, a thermal cycler, a liquid-handling robot, it doesn't matter which. The features provided by the manufacturer do not fit her unique needs, and there is no hope whatsoever of altering the instrument or building her own. Learning to tune the instrument's parameters did not teach her anything about how the instrument actually works. Science is about venturing into the unknown, where everyone's needs are unique. But these researchers are using mass-produced tools which cannot be *learned from, changed, or extended*.

Physical reality

A researcher designs a nanostructure. A nanostructure is a physical object with a physical shape, but the researcher never gets to feel that shape with her hands. Instead, she draws lines on a screen. She designs a biological circuit. The cells, viruses, and plasmids are all physical agents that interact with each other, but she never directly experiences these dynamics. Instead, she types text into a screen. She looks at data from the electron microscope and sees views of a physical landscape of particles, but she cannot walk within that landscape and explore it from within. She clicks buttons on a screen.

She presents a seminar to colleagues. Her conclusions are based on a deep exploration of the data, but her colleagues cannot walk around in the data and explore it with her. They watch a slideshow with low-density summary plots, and ask questions from their chairs.

The researcher plans her experiments, analyzes their results, and communicates them to colleagues — all within a computer screen. But her cells and molecules, plates and test tubes, gel boxes and centrifuges — all of these are out in the real world, not inside a screen. Science is about forming an intimate connection with the physical world, but computational tools confine scientists to artificial worlds of their own.

In-person collaboration

A researcher works at a computer screen. Her colleague works with her... how? Sitting behind her shoulder, backseat driving? Or sitting at a separate screen entirely? Either way, they're not really working *together*. They can't make eye contact. They can't get their hands on the same thing. They can't get their hands on *anything*.

A computer workstation is an isolation chamber. It denies face-to-face interaction, shared hands-on work, tacit knowledge, mutual context, and generally being present in the same reality.

To have a discussion, the researchers *leave the computer*. They get a coffee, and have an entirely verbal discussion where they cannot explore computational models, examine data, or consult references. They wave their hands around, and occasionally disappear into their phones.

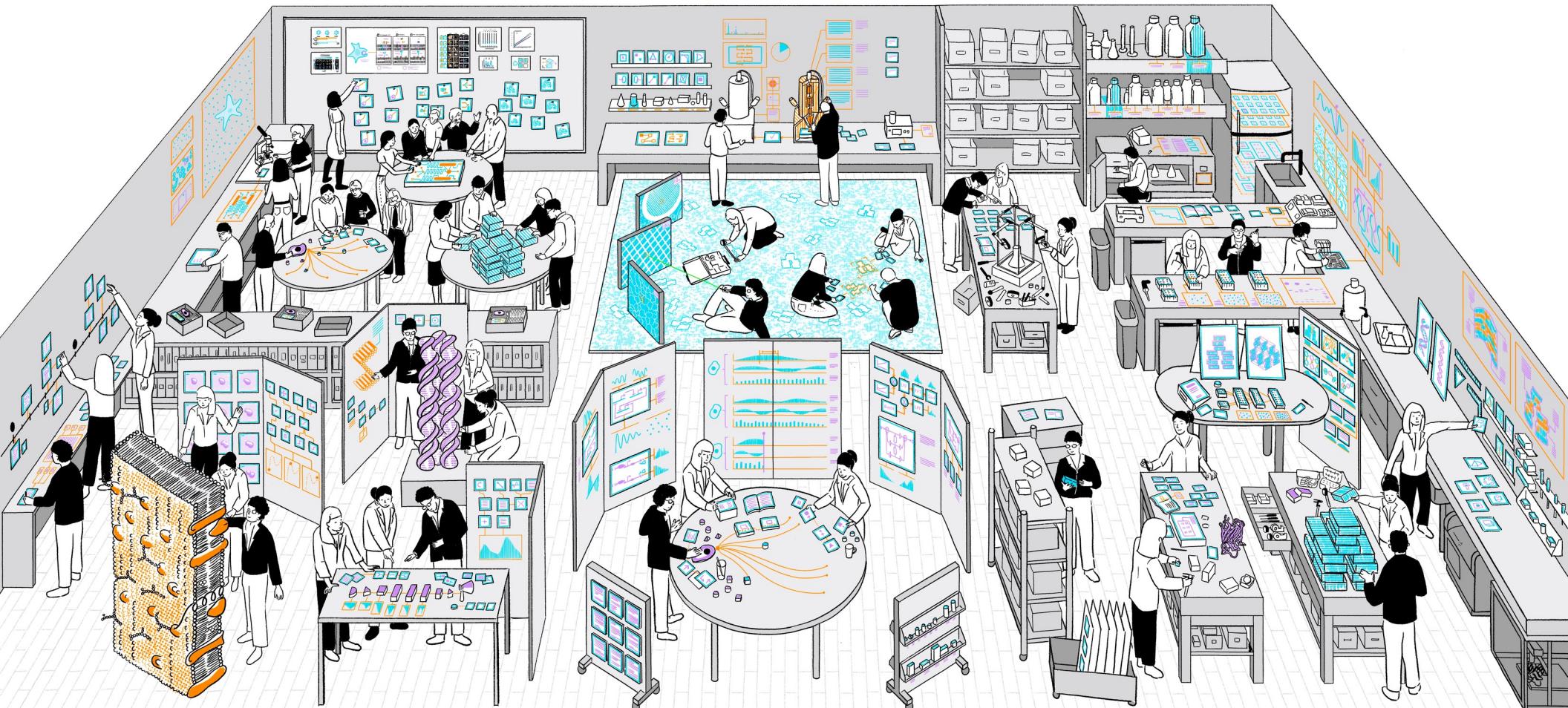
In a computerized lab, working "together" really means working *adjacently*. Without the visibility to see what others are doing, without the agency to build tools together, without the connection to reality that would let them actually do science in a shared setting, each researcher separately pursues their own part of the project. They combine each other's results without gaining each other's knowledge.

The communal science lab

6. Presentation

5. Analysis

4. Fabrication



1. Orientation



2. Modeling



3. Design



Communal computing

The problems of the standard science lab are not unavoidable consequences of using computation. They arise from an accident of history — how computers, and the practices around them, happened to evolve.

We believe that the solution requires the invention of a new form of computing, designed from the ground up around

visibility

agency

physical reality

in-person collaboration

For several years, we have been doing all of our day-to-day work in such a computing environment. In *Realtalk*, our research operating system, there are no screens and no apps. Instead, computational tools are physical materials in physical space, which are recognized and illuminated by cameras and projectors in the ceiling. All work takes place out on tables and walls, including programming the computing system itself.

People work together face-to-face, getting their hands on the same things. Collaboration happens easily, spontaneously, and constantly. Computation can take up as much space as necessary, even filling rooms, and naturally integrates with physical instruments and devices. Because everything is out and visible, people readily learn from and build upon other's work.

Computational complexity is reduced by orders of magnitude, and many useful tools are one or two-page programs. Tools are simple enough that people make their own, and understand those of others.

For several years, we ran *Dynamicland*, a community workspace built around Realtalk, where thousands of people experienced working this way, and hundreds of substantial projects were built. Having seen, firsthand and repeatedly, how transformative this form of computing is in the hands of a wide variety of people, we are eager to see it transform the practice of science.

Communal science

In our vision of communal science, researchers from different backgrounds easily work together to take on cross-disciplinary projects that would otherwise be out of reach.

These collaborators all learn each other's expertise by jointly constructing computational models, with their hands, that represent their shared knowledge and simulate their ideas. These models are physical things that pervade the space; they are the work environment for the project.

The researchers design the tools they need, together, improvisationally, recombining components in new ways or whipping up new components on scratch paper. What would traditionally be a complex monolithic app, they put together in a day. The next day, they take it apart and rebuild it to answer the next set of questions.

Instruments are improvised in the same way, because there is no boundary between computational tools and physical tools. While performing an experiment, the researchers remix their instruments, and program the lab bench itself. They program the entire room, giving everyone a clear view of the physical processes going on, at all scales, at all times.

To share their findings, the researchers invite colleagues into their space of computational models, give them a tour, and let them explore the data for themselves. Through hands-on side-by-side exploration, colleagues from distant fields learn enough to actually understand the details of the project, and come up with ideas for collaboration.

The scenario on the following pages suggests how one specific project might proceed in a communal science lab.



1. Orientation

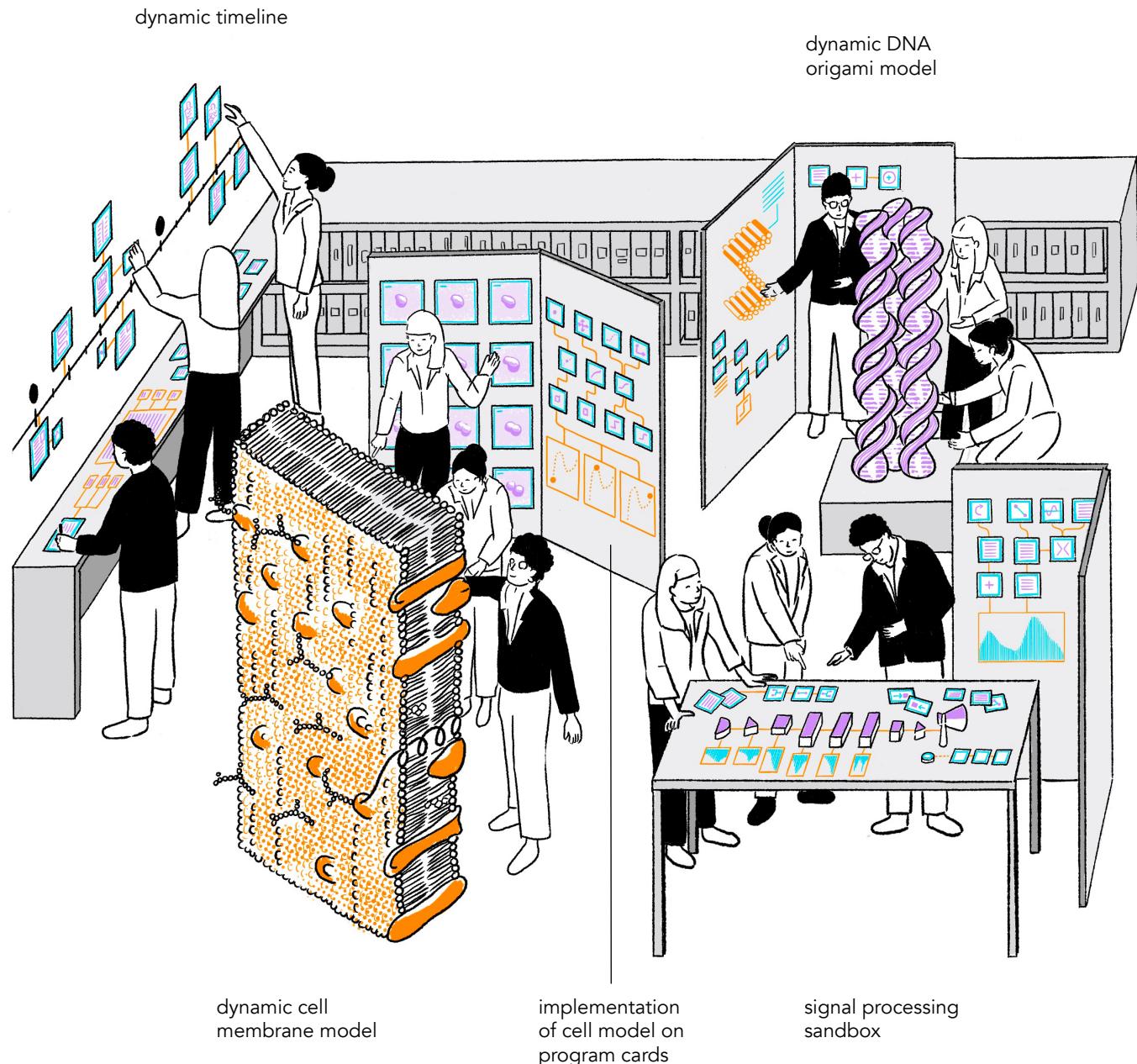
A cell biologist, electrical engineer, and nanoscientist have come together to create a new kind of biochip for studying cell behavior. They're eager and excited by the potential of this collaboration, but also feel a bit lost. They barely know anything about each others' fields, and have no idea what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

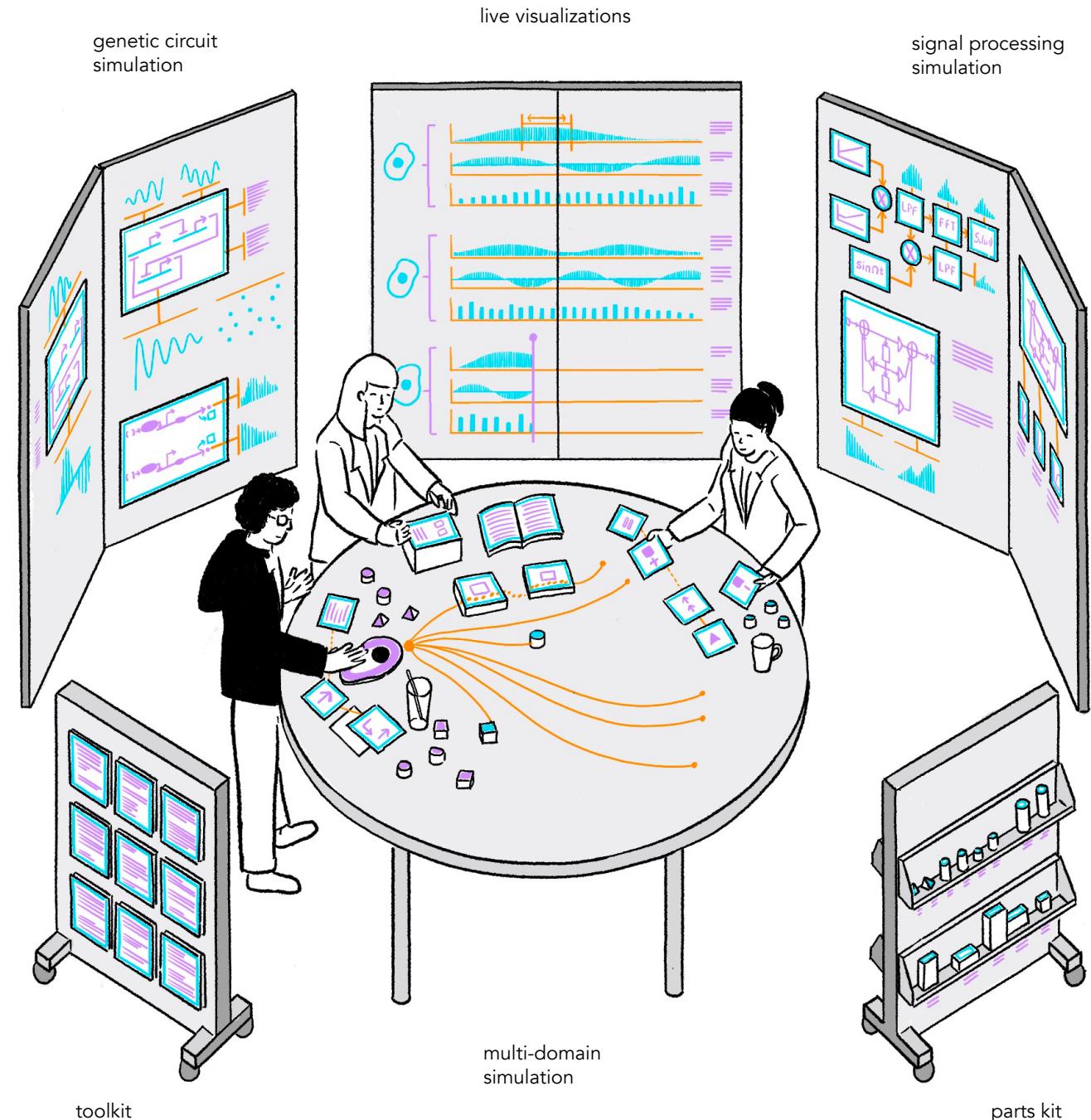
The three researchers have a plan, but it's a vague image in their heads, and further conversation reveals that they're each thinking of something different. To get in sync, they set up a space to build a **whole-system simulation**.

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

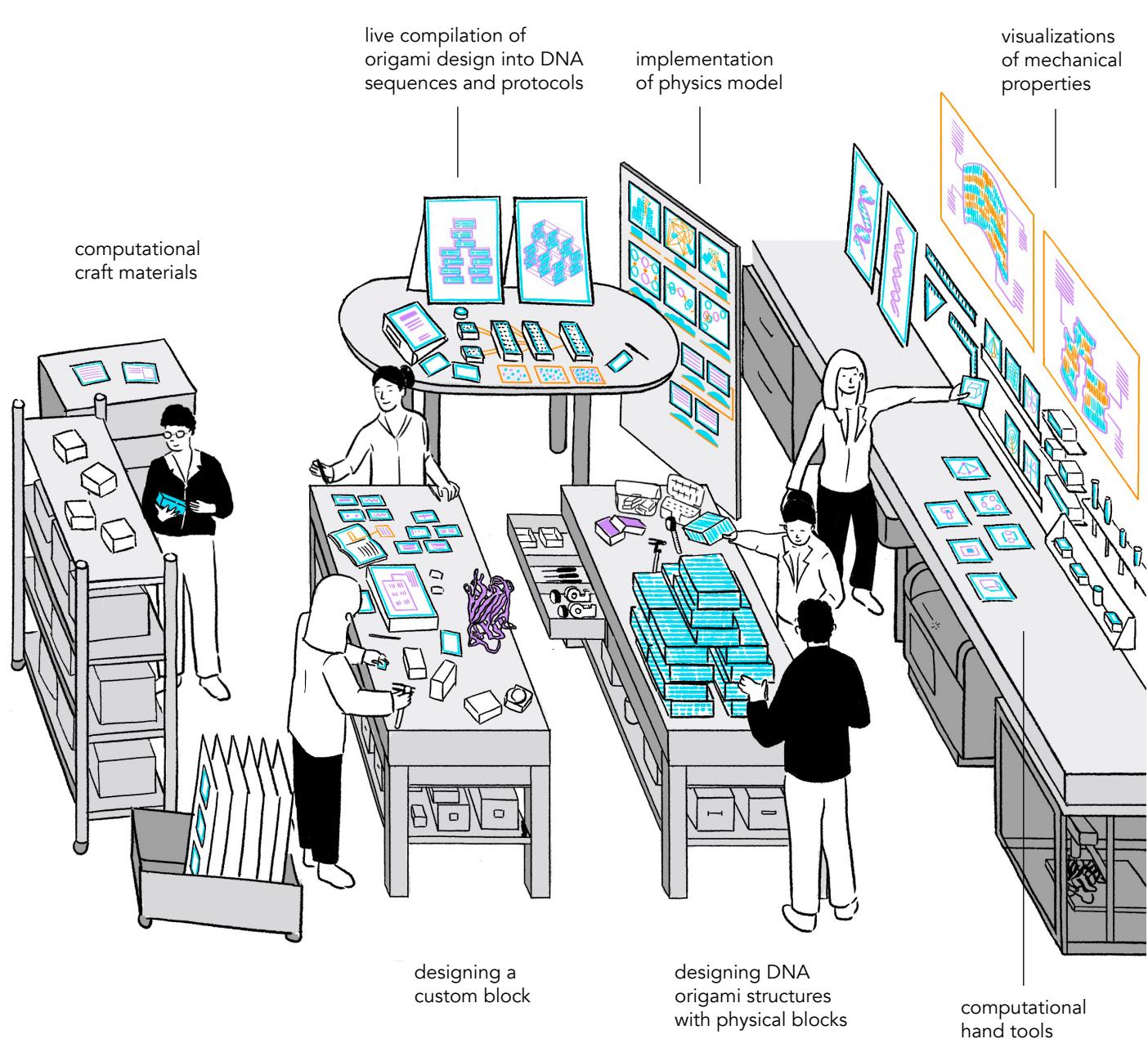
The three researchers start designing the DNA origami nanostructure for the substrate of their biochip. As they snap together blocks to construct a **scale model**, live simulations display their design's mechanical properties. The biologist and engineer have never worked with DNA before, but they find 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

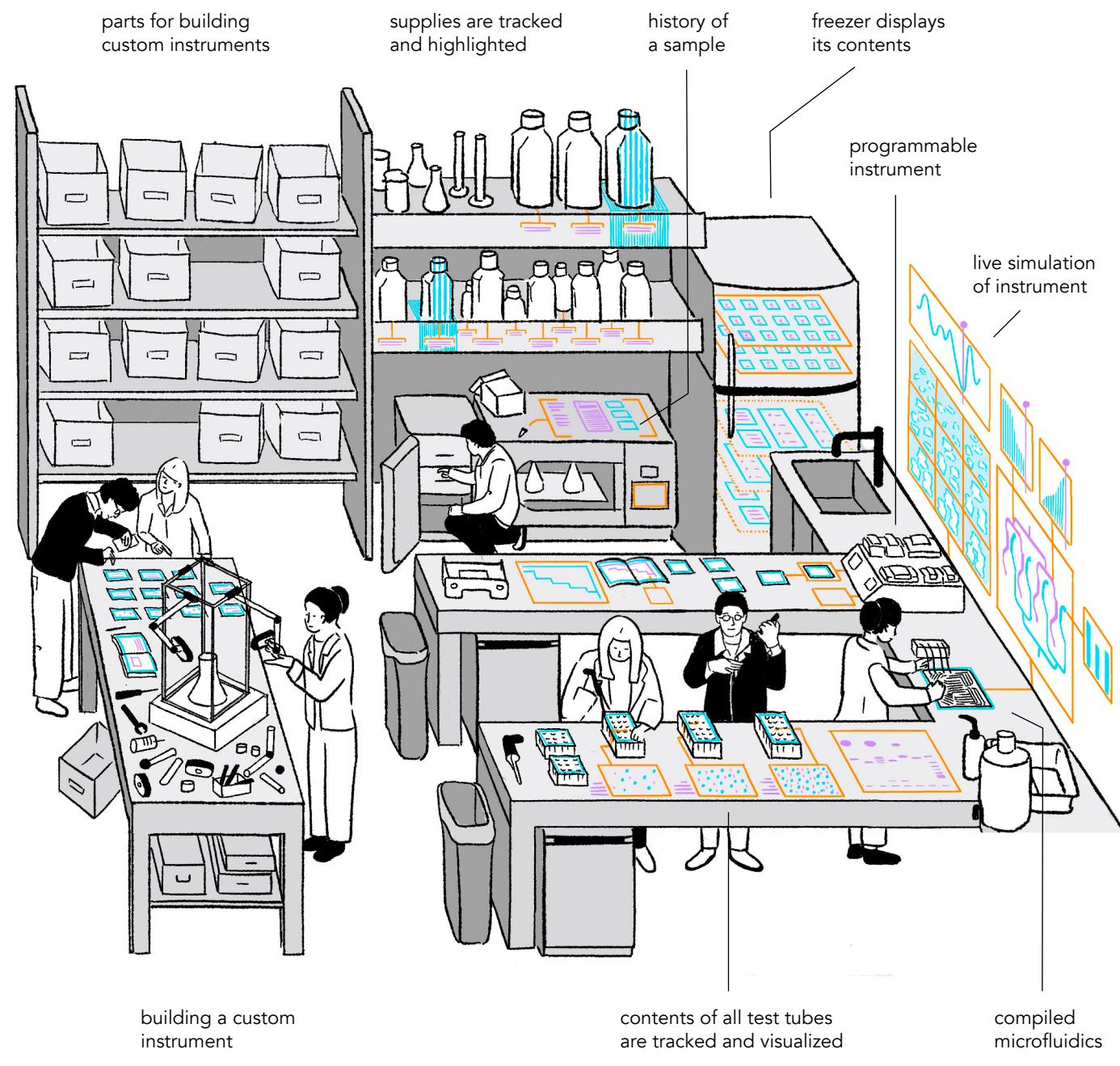
As the researchers carry their designs into the wet lab, the entire room lights up, configured for this protocol. A freezer beckons the engineer to take out a tube of scaffold DNA, and the tube fans out a **history** of how the sample was made and used. The engineer curiously flips through some of this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

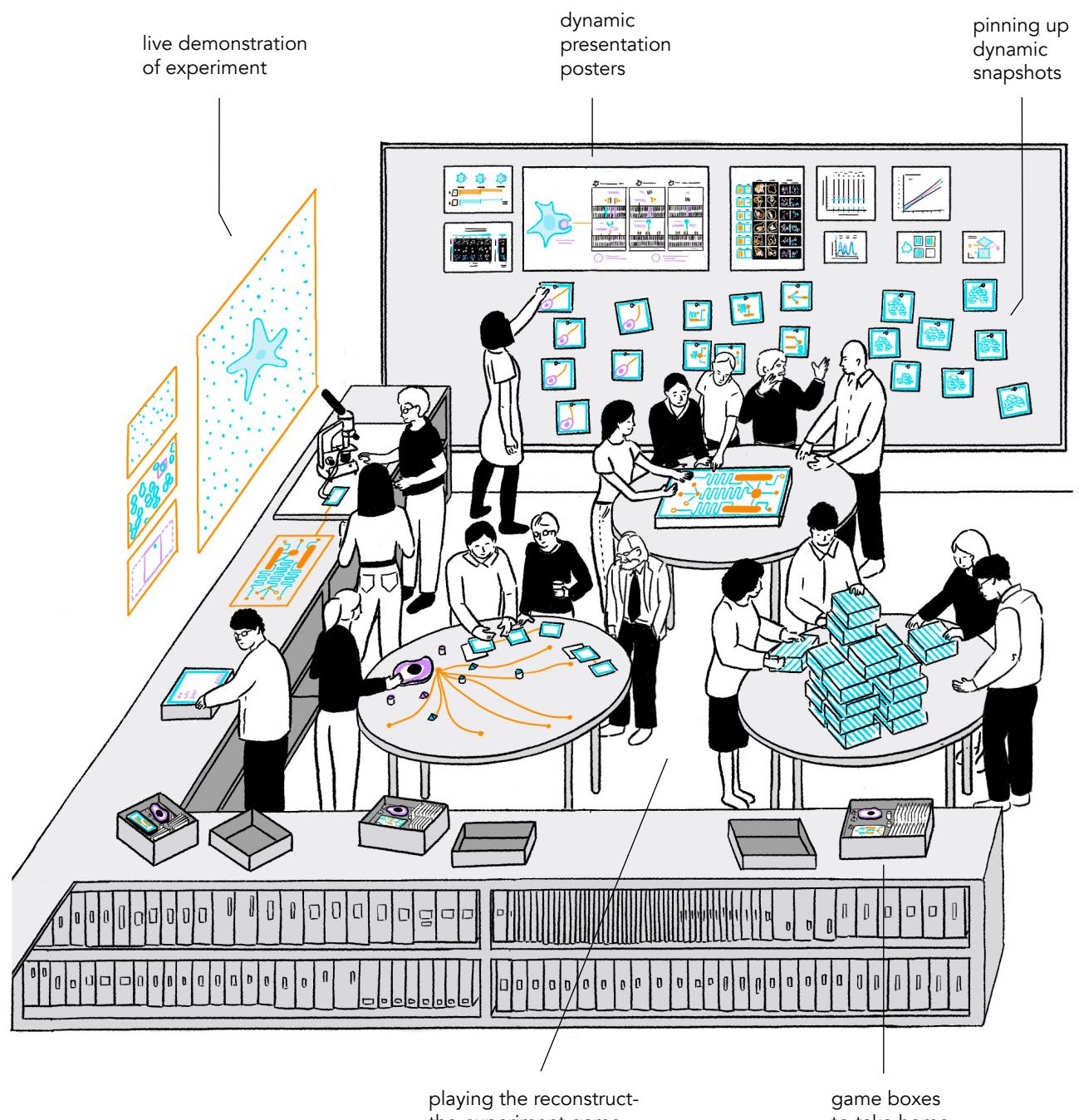
It begins with a **walking tour** through their dynamic models, showing and telling, recounting stories, immersing the audience in data and evidence, getting them excited about the discovery. But it's not enough for the audience to just appreciate the work. They have to understand it deeply enough to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



Prior work: Realtalk



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

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. Many 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 people that use them. 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: 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.

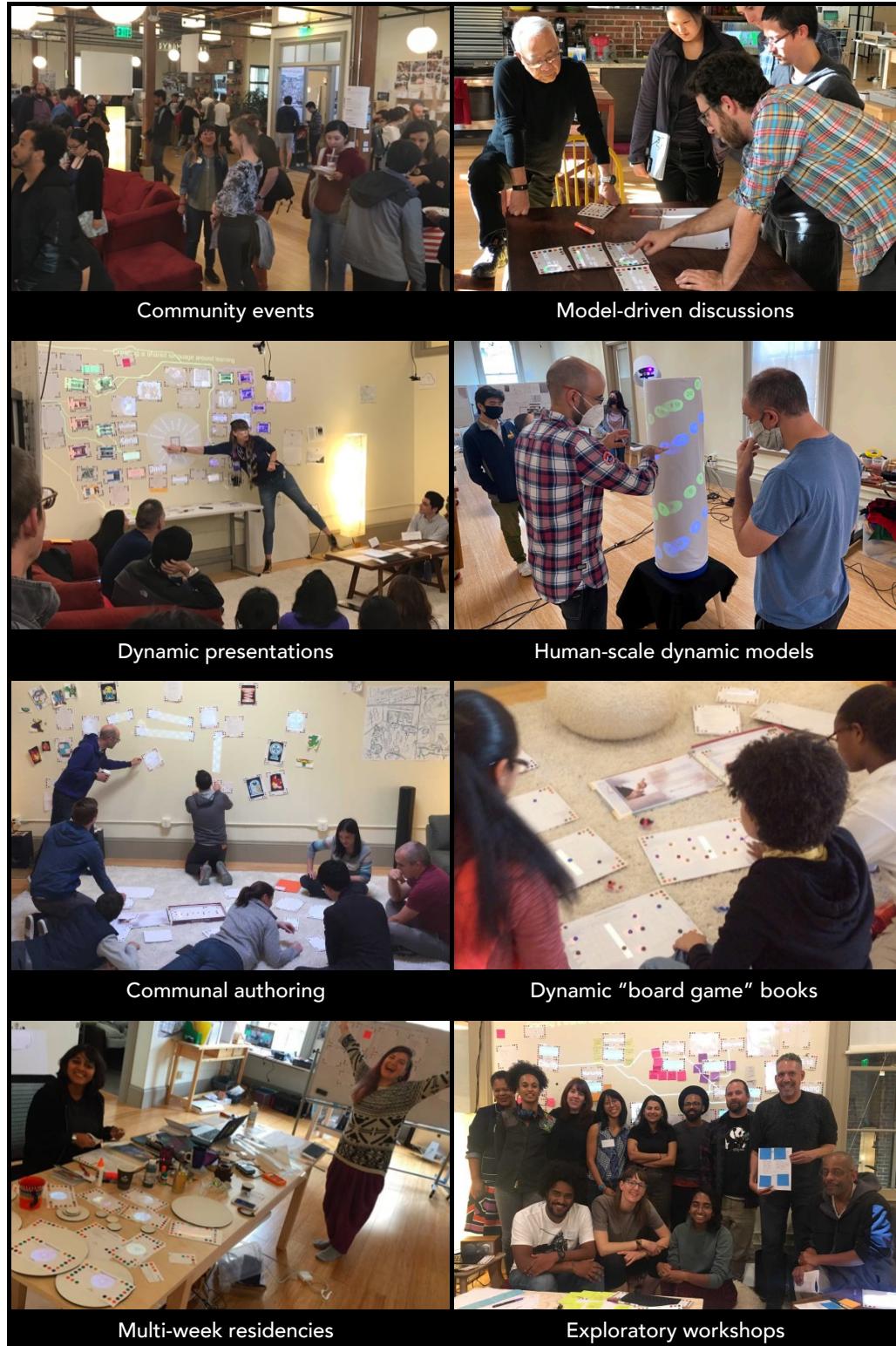
Dynamicland was designed to give the community total agency within the system. A tool wall collected useful apparatus for manipulating and editing dynamic models, and community members came to know these tools as intimately as carpenters in a wood shop. A tutorial gallery held dynamic books teaching 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.

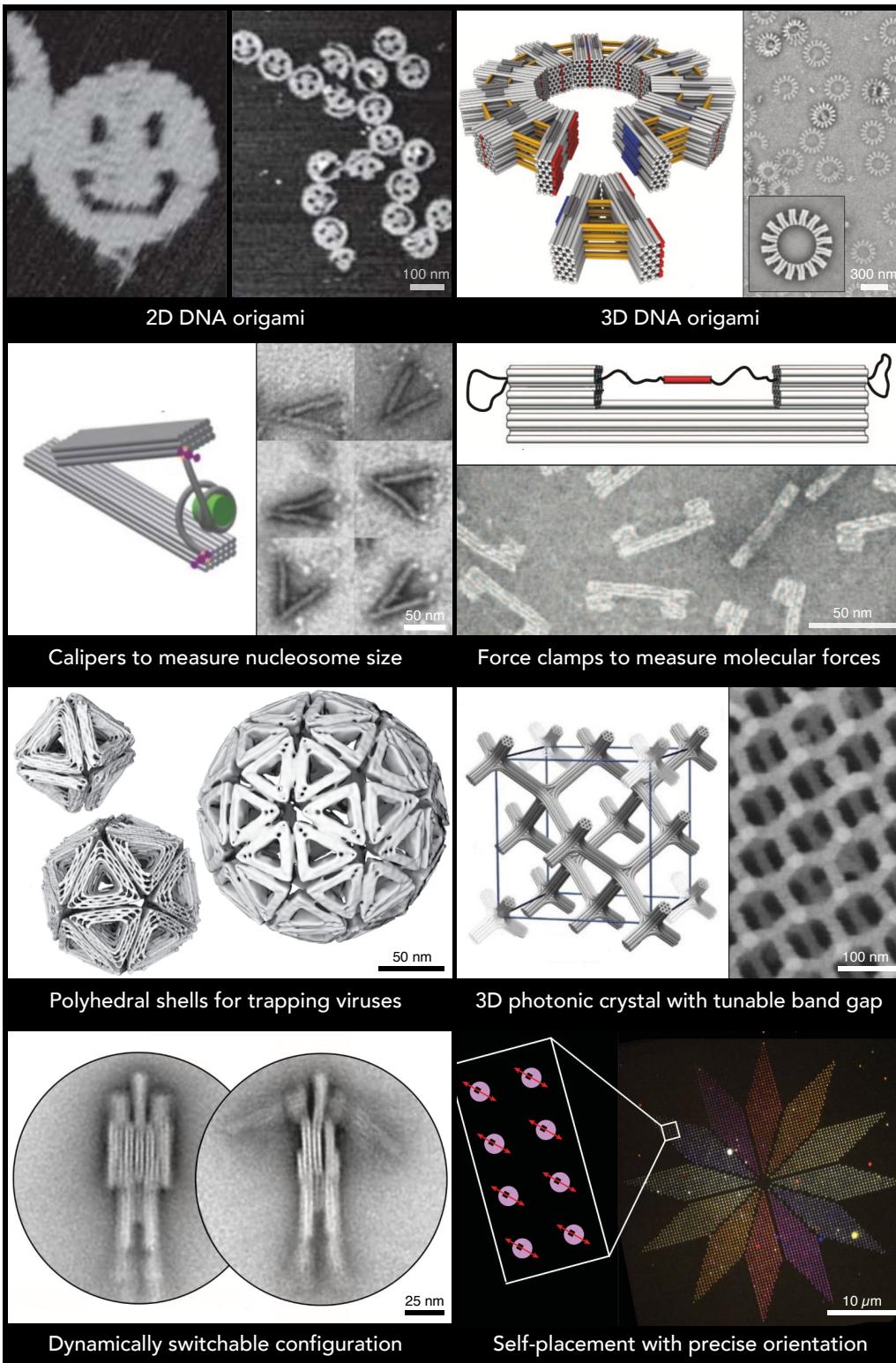
On a given day, you might find a community member building a prismatic light simulation on one table, while a group nearby explored the harmonic relationships between different scales of music. A dynamic graph of social and economic data was connected to a dynamic map, which connected to a live satellite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

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: DNA nanotechnology

An ideal scientific context for pioneering communal science

DNA nanotechnology is the science of designing and producing extremely tiny objects, 10 to 100 nanometers in size — 100 times smaller than a human blood cell. An analogy might be 3D printing, but instead of being sculpted by a machine, these tiny devices assemble themselves. By mixing readily-available ingredients and “baking” for a day, we get one trillion identical precisely-defined shapes in the volume of a raindrop.

DNA origami is a particularly versatile method, in which a long strand of DNA is made to fold into any desired shape by pinning it with short “staple” strands. Because every part of this shape has a unique DNA sequence that other molecules can bind to, it can function as a “jig” to hold specific materials at precisely-defined positions with atomic resolution. This task is extremely difficult with any other technology.

Since its invention in 2006, DNA origami has found numerous and varied applications. These include tools for manipulating and measuring molecules (tiny clamps, calipers, force sensors, nanopores), robotic devices (tiny rotary motors, hinges, tracks for molecular walkers), targeted drug delivery, and other applications across medicine, biology, electronics, computer science, and more.

We believe there is no better field in which to pioneer a communal science lab. It’s about *building* physical structures and *looking* at them, which invokes the full feedback loop of design, fabrication, and analysis. Researchers need the **agency** to create custom design and analysis tools, and extreme **visibility** to see and understand what they’ve designed, both in simulation and in reality.

Human-scale clamps and calipers let us work with human-scale structures. To understand and work with anything in the biomolecular realm, we need tools at biomolecular scale. Tiny tools give us a direct connection to a nanoscale **physical reality** that is otherwise inaccessible. And DNA origami is an integration technology — it binds together materials from many fields. It’s therefore inherently interdisciplinary, bringing together *people* across many fields, a perfect setting for **in-person collaboration**.

More information

What is bionanotechnology? (7 min)
dynamicland.org/links/2011-03-07

Image sources on p.23

Prior work: Douglas Lab

Experiences and challenges in advancing a field

One of us (Douglas) got involved with DNA origami immediately after its debut, co-inventing the 3D version of the method, and demonstrating the first DNA-based nanorobot for targeted drug delivery.

In 2009, he released Cadnano, an open-source computer-aided design tool for DNA origami. The impact of this work was immediate and significant:

Cadnano reduced the time needed to design a new nanostructure from one month to one afternoon. It has since been downloaded over 35,000 times and cited by more than 1300 papers. It catalyzed significant and rapid progress in the field of DNA nanotechnology, and remains the standard platform for DNA origami researchers worldwide.

Douglas's further work significantly advanced the technology, including a method for producing custom single-stranded DNA (enabling designs with non-biological sequences) and a thermodynamic optimization algorithm which improves yields by an order of magnitude. He also pioneered applications with collaborators across many fields, including molecular goniometers for high-resolution imaging of proteins with cryogenic electron microscopy, and precisely-controlled nano-environments for studying cell behavior.

His experience with Cadnano has made him acutely aware of the obstacles to creating, maintaining, and improving scientific software as it currently exists. And running a lab has made him aware of the challenges in training new researchers, group communication, and collaborating across disciplines.

In 2011, he founded BIOMOD, a global design competition in which over 1600 students from 15 countries have gained hands-on experience in cutting-edge nanotechnology. In 2018, he released Gelbox, a simulation and visualization tool to help trainees understand gel electrophoresis, the field's primary diagnostic. These are just two of an ongoing series of attempts to introduce tools to improve how scientists learn and collaborate.

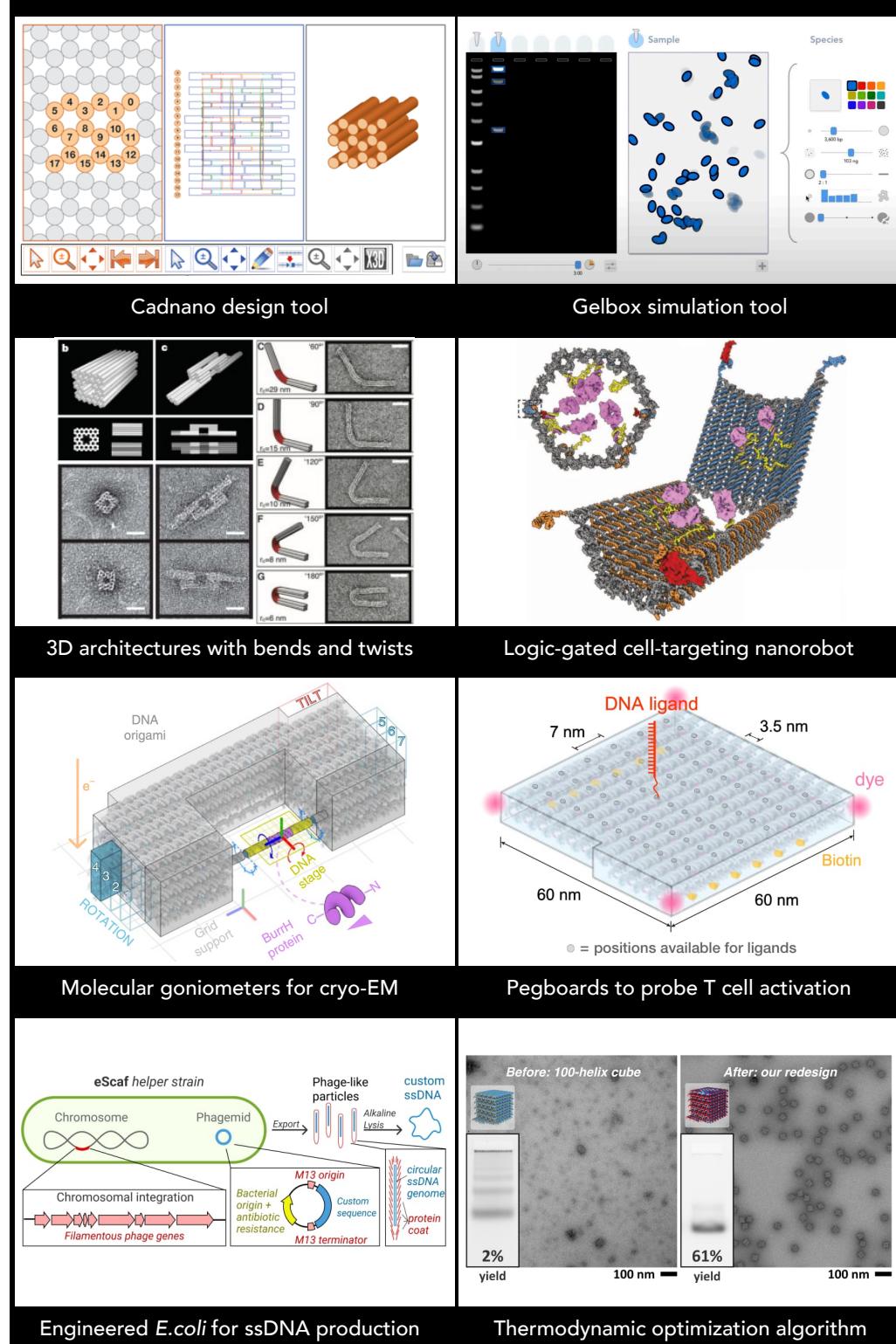
He now sees Reatack as the most promising approach to both the software challenges and collaboration challenges in the lab.

More information

Douglas Lab
bionano.ucsf.edu

Cadnano
cadnano.org

Gelbox
douglaslab.org/gelbox



Prior work: Biomolecular design 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.

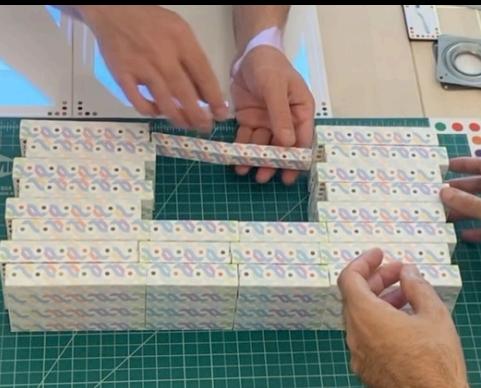
In the wet lab, we prototyped a turn-by-turn navigation system for fabricating these designs, with projections revealing precisely what was in each test tube, and what to pipette, where, and how much at each step. Using a laser pointer, we could point at any instruction or object to identify reagents, 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 by anyone at any time. This was a striking contrast to our widely-used open source tool Cadnano, whose code has almost never been examined or modified by its users.

The scenario depicted earlier extends directly from what we learned during this prototyping experience.



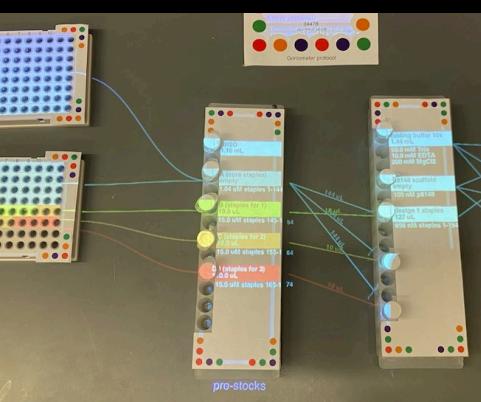
Designing proteins together
on the table.



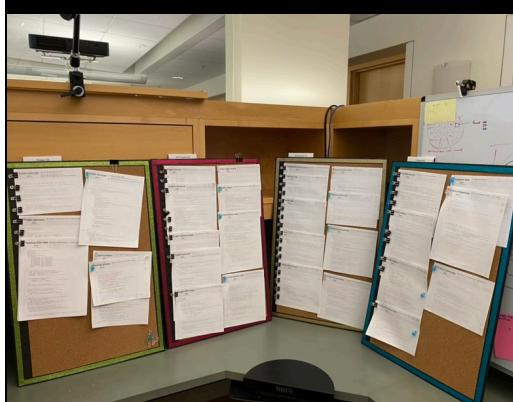
Designing a DNA nanostructure
using physical blocks.



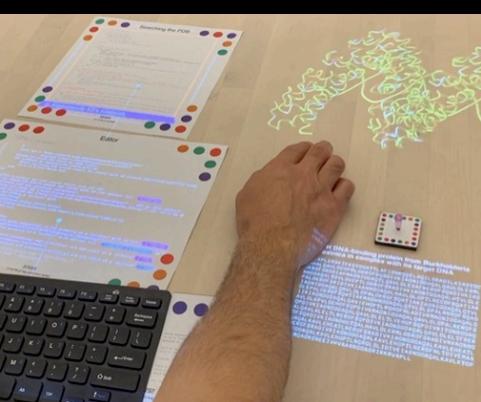
Pipetting with turn-by-turn navigation.



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.

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

Prior work: A communal presentation

Realtalk at a scientific conference

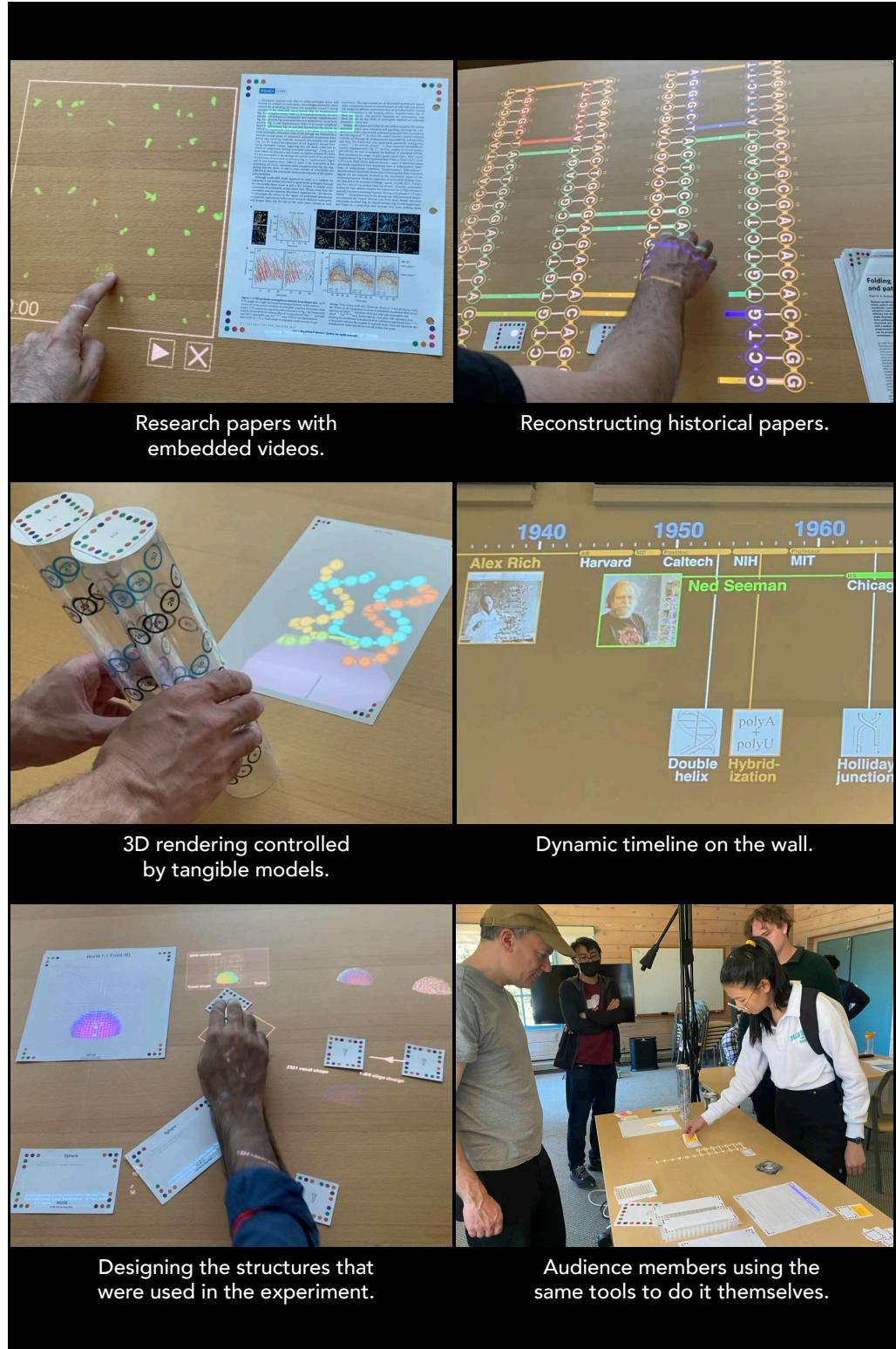
In 2023, we brought Realtalk to a scientific conference and gave a presentation within it. Instead of clicking through slides, all action took place out on the table. We explained the context of the latest experiment by spreading out physical research papers with our hands, and pointing into them to play embedded videos.

Because most of the audience was unfamiliar with DNA nanotechnology, we answered the question “How did people ever figure out how to do this?” with a history of the seminal papers in the field. Instead of just talking about them, we *reconstructed* them — building and visualizing the structures they described, live on the table, with a small deck of dynamic cards. We also told the stories of the key people involved, with a persistent dynamic timeline of their lives along a side wall.

We then presented the lab’s latest work. Instead of just talking about the structures used in our experiment, we actually designed them, live on the table. Our fabrication-ready tools live-generated a set of DNA sequences, a cost estimate for the materials, and a protocol which could be taken to the wet lab. The entire implementation of this design environment fits on a single posterboard.

After the presentation, we set up Realtalk in another room so audience members could try what they had seen for themselves. We coached students through making their own constructions, and they were delighted to gain a hands-on understanding of DNA concepts that they had only read about.

Back at the lab, we still pull out these presentation materials in discussions with colleagues and funders. They fit naturally into the flow of conversation, and the conversation continues with the materials on the table — a very different feeling than everyone crowding around a laptop or phone.



More information

Improvising cellular playgrounds in Realtalk (15 min summary + 1 hour)
dynamicland.org/links/2023-08-09

The path forward

2024: The first communal science project

As compelling as they were, our biotech prototypes were unfunded side projects, inspired by but not directly connected to real work in the lab.

In July 2024, we received a two-year grant to integrate Realtalk into the day-to-day work of the lab, and carry out — for the first time ever — a real science project in a communal computing environment. We are beyond excited to experience doing actual scientific work in Realtalk, and take the first steps in the transformation to a communal science lab.

The science project will involve a wide variety of activities, all of which seem ripe for a communal approach. We'll be designing novel kinds of nanostructures, simulating their physical characteristics, fabricating them in the wet lab, growing and processing cell cultures, collecting and analyzing data from gel electrophoresis and electron microscopy, and trying to understand the results well enough to plan the next iteration of designs and experiments.

We are filled with ideas for how this conventionally-solo work can be done by multiple people working together with their hands, how we'll improvise small composable tools that everyone can see and understand, how we'll bring computation into the physical world of the lab bench and see what has always been invisible, how we'll cover the space in data to explore and discuss together.

Like any science project, communication among people will be just as important as working with molecules. We'll be holding group meetings in Realtalk, so we can explore computational models together and browse previous experiments and data. We'll host workshops in which newcomers will be introduced to the field by constructing and exploring tangible computational models. At the field's annual conference, we'll present our project in the form of an immersive exhibit. And although the paper we submit for publication will necessarily be a conventional PDF, it will have been organized and composed in the real world.

All of this will be unprecedented. Nobody else is doing anything like this.

We intend for the practices and processes that we invent while doing this project to form the seed of a radically new way of doing science.

2030: The molecular makerspace

From the seed of a single project in a single lab, we will gradually grow a communal scientific culture. Initially, through adjacent in-person collaborations — workshops, conferences, collaborative projects.

But the next major step will be the founding of a new lab dedicated entirely to incubating communal science.

- 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 specialty, 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* and get immediate benefits, without a major investment or commitment.
- To rapidly evolve the platform, there must be *rapid feedback cycles* of exploration, design, experiment, and analysis.

These criteria suggest a vision of a *molecular makerspace*. Scientists across a wide range of fields will visit for short-term residencies, to collaborate on cross-disciplinary projects which would not be feasible elsewhere. Residents will learn to use cutting-edge molecular technology to integrate their materials on the nanoscale, within a cutting-edge computational environment for integrating their ideas and knowledge on the human scale.

While we expect these collaborations to yield valuable results, their deeper purpose is to provide the context for evolving the culture. The primary research of the lab's staff will be at the meta level — tending the community and continuously improving the computing environment, the molecular technology, and the cultural practices around them.

There will be a constant flux of visitors passing through and experiencing communal 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 communal science into common practice.

2040: The network of dynamic knowledge

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.

After working at the molecular makerspace and internalizing the culture, one researcher will go home inspired to start their own communal lab. This lab will be the second node in a new *network of dynamic knowledge*.

The second site will carry the culture of the first lab by inheriting some of the dozens of researchers now fluent in the dynamic medium, and will be seeded with the hundreds of dynamic models accumulated in the first site's library. Over time, it will contribute back its own creations and discoveries.

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 culture of communal science will spread first to peer laboratories and community spaces, then to universities and public good institutions, and over the following 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*.

2050: Visions from a communal 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.

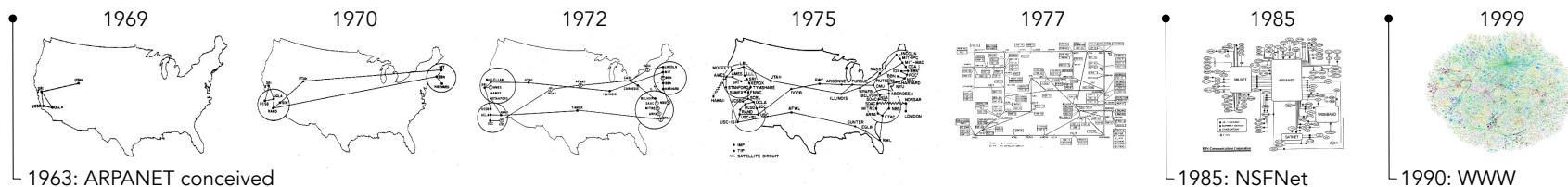
At a nearby public library, a community has gathered to understand a local nutritional health deficit. Through discussion they trace the root cause to a shortage of fresh produce caused by surrounding drought conditions. Adapting an agricultural model from a neighboring town, they rapidly fabricate topological maps of their community to find the best locations for 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.

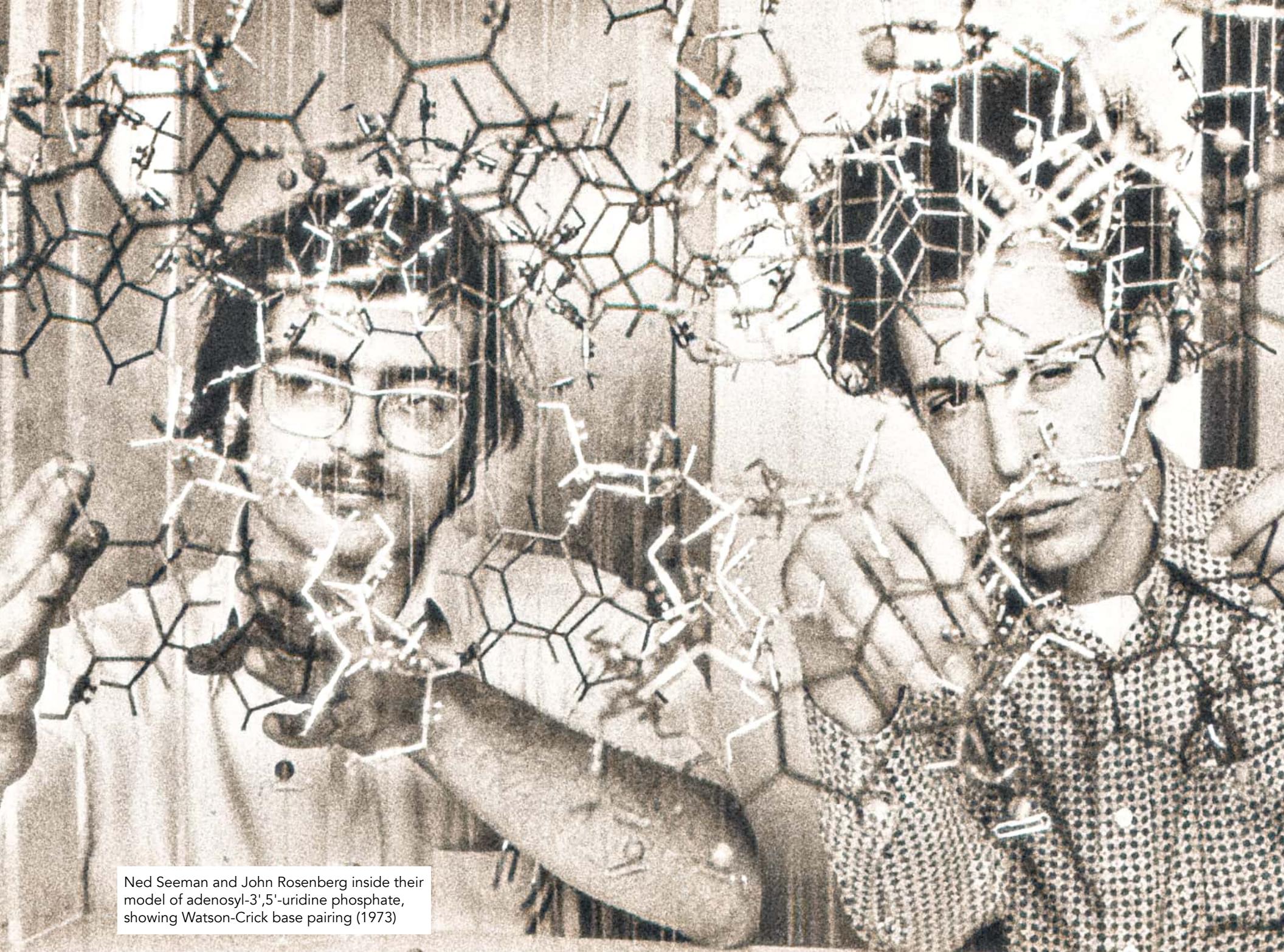
When the simulation shows the water usage of these gardens may add too much load to an already-strained municipal water system, a dynamic book on rainwater harvesting systems shows possible solutions — they determine the needed water collection surface area needs and cistern volumes while scrubbing through 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 local 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 and old forms of ecological knowledge, technology and infrastructure must be invented, rediscovered, 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 millennia — 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 and caretakers will collaborate to build a world that is not only sustainable, but flourishing.

ARPANET to Internet, 1969-1999





Ned Seeman and John Rosenberg inside their model of adenosyl-3',5'-uridine phosphate, showing Watson-Crick base pairing (1973)

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Bret Victor

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

Previously at Apple, he designed the earliest 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., 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 iPad, and built immersive exhibits at the 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 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 careers.

July 2024

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