REGENERATIVE ARCHITECTURE
BIOLOGY, INNOVATION, AND THE BUILT ENVIRONMENT

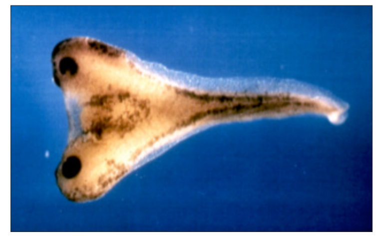
David Benjamin and **Ali Brivanlou** (Professors), with **Danil Nagy** and **Jesse Blankenship** (Software Consultants)

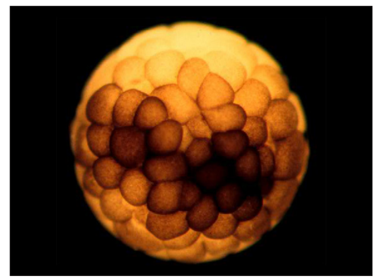
"The biggest innovations of the twenty-first century will be the intersection of biology and technology." (Steve Jobs)

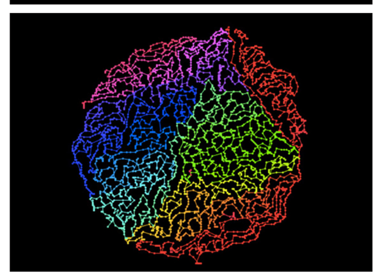
"Biological and organic forms that do not exist in the natural world can be created in the lab." (Ali Brivanlou)

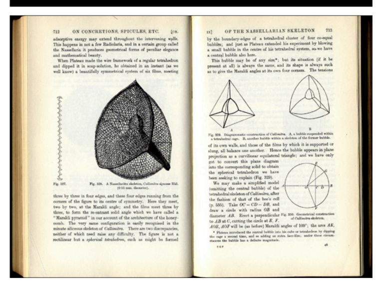
"Over the next 20 years, synthetic genomics is going to be the standard for making anything." (Craig Venter)

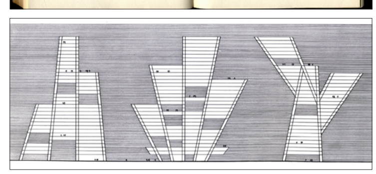
1. OVERVIEW

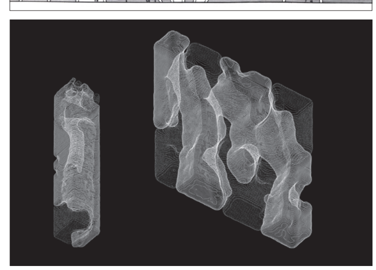












Images (top to bottom): Two-headed tadpole created in the Ali Brovanlou Lab; Tadpole embryo at 128 cells (Ali Brivanlou); Data visualization of growth of bacterial colony (Lars Dietrich Lab, David Benjamin, Danil Nagy, ADVP); On Growth and Form *(D'Arcy Wentworth Thompson, 1917); Cross sections for free-span sections of tall buildings (Heinrich Engel); Structures created through reaction diffusion behavior (Sydney Talcott, GSAPP Bio Design Studio 2013).*

Biological growth has fascinated architects for centuries. But recent developments in our understanding of biological systems—and our ability to gather data from them, model them in the computer, and directly manipulate them—have opened up startling possibilities to **actively integrate biology and design**. This unique advanced architecture studio, co-taught by architect David Benjamin and developmental biologist Ali Brivanlou, leaps to the forefront of new collaborations between architecture and biology, and aims to produce novel examples of how they may affect our **buildings of the future**.

2. DYNAMIC ARCHITECTURE

Natural shapes change with time. Human structures are static and inert.

Natural selection based on an infinite number of random variations has produced the kind of dynamic systems that allow embryonic cells to **adapt** to both the inside environment of the embryo ("milieu interieur"), and the outside environment (pond water in the case of tadpoles). This process has allowed the evolution of the most robust dynamic systems. For example, vertebrate embryos converge toward the same morphology at a given point regardless of their original shape.

In this studio, we propose to **bring human architectural designs to life as dynamic systems**. To do this, we will use the logic of embryonic pattern formation and the rules of morphogenesis. Foreshadowing a **new generation of bio architects**, students will use the logic of cell growth, differentiation, and morphogenetic movements to program dynamic architecture.

3. BEYOND BIOMIMICRY

The integration of embryology and architecture, which seems *a priori* obvious, has somehow not been exploited to date. Yet it promises to have a **transformative**

influence in both fields. This will represent a progress long overdue. The creation of dynamic architecture will allow structures to adapt to their ever-changing environmental conditions. This may result in buildings with more efficient energy consumption, **more fluid relationships** with occupants, and **more synergistic interactions** with other buildings and the broader city. More specifically, it may produce structures grown from a single cell, buildings that dynamically evolve in response to surrounding buildings, cities that exchange materials and energy in complex ecosystems, building facades that **regenerate and self-repair**, and architecture that **self-replicates**.

Buildings no longer need to be static and inert. Building materials no longer need to be produced by methods of heat, beat, and treat. Architects can begin to collaborate with natural systems rather than resist them. They can engage **reciprocal flows of resources and energy**. They can develop radical new design practices to meet the radical challenges and opportunities of our dynamic times.

4. THE CENTURY OF BIOLOGY

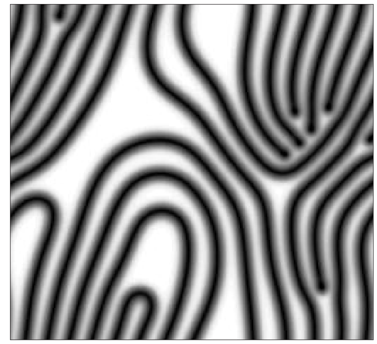
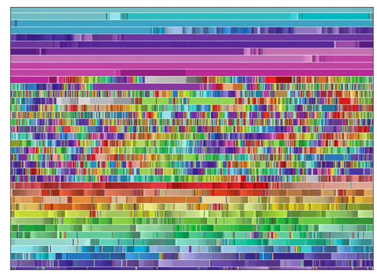
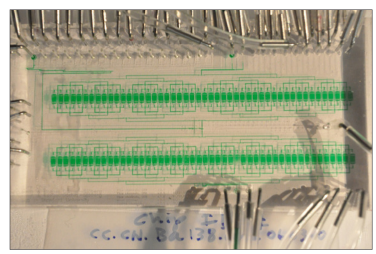
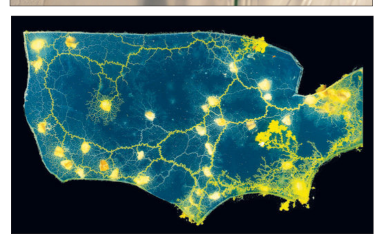
If the Twentieth Century was the century of physics, then the Twenty-First Century is the **century of biology**. Biological tools and technologies are advancing at a staggering pace. The cost of sequencing DNA and synthesizing DNA is decreasing by 50% every 18 months, following a curve similar to Moore's Law for computer processors.

New techniques make it possible to track individual cells inside living organisms (through quantum dots), to monitor communication between cells in real time (through 30 simultaneous microscopes and software to control them), and to measure and understand the influence of molecular and genetic changes on biological growth and behavior.

Further, **it is now possible to manipulate biological organisms in revolutionary ways**. Forms that do not exist in the natural world can be generated in the lab. We may be at the beginning of a **new era of biological design** that will transform all aspects of our world, including the built environment.

5. ORGANISMS AS PARAMETRIC MODELS

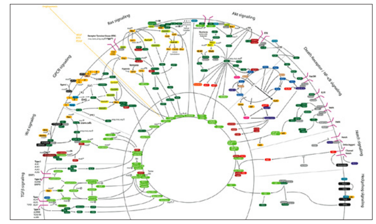
As it becomes possible to manipulate the genome of an organism and then measure its success at performing a specific task, as well as encapsulate this behavior in software, we can think of **organisms as parametric models**. Change

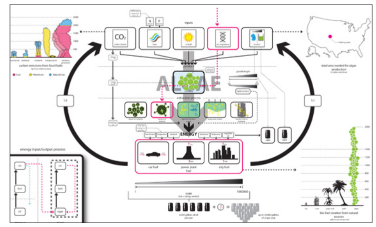






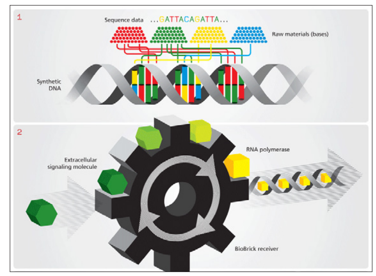
Images (top to bottom): Material Ecology (Neri Oxman); Reaction diffusion pattern; Data visualization of wikipedia edits (Fernanda B. Viegas, Martin Wattenburg, Kate Hollenbach); Custom microfluidics and imaging machine (Ali Brivanlou Lab); Adaptive network design through slime mold computing (Andy Adamatsky); Ecosystem of living and non-living growth (The Living, David Benjamin); Breathing building envelope (The Living, David Benjamin).

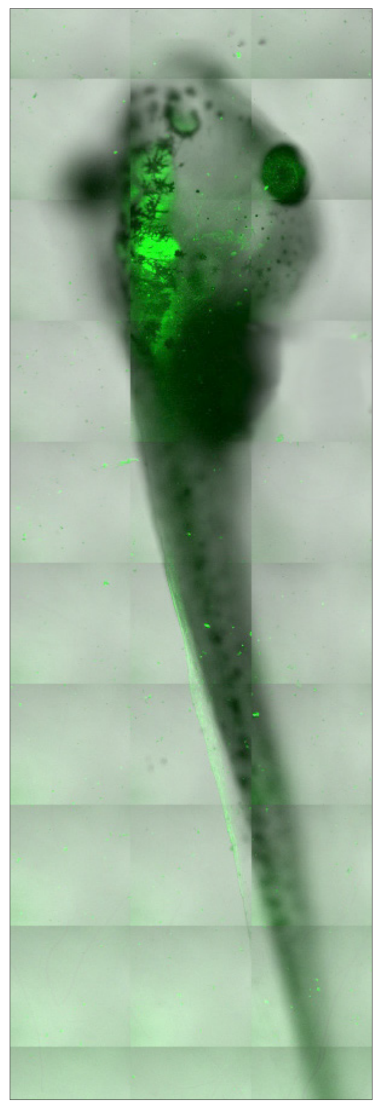
the input—the A, T, C, G of genetic code—and derive a different output. In one existing project, researchers are varying the parameters of 20 different genes in microalgae to search for the design permutation that creates the greatest amount of clean biofuel. Increasingly, architects may be able to manipulate parametric models to explore new biological systems.

Our studio will directly build on design workflows for parametric modeling developed in a prior series of studios at GSAPP. Students will learn to use some of the same software tools for **geometric modeling**, **digital simulation**, **evolutionary computing**, and **optimization**. But they will extend this prior research into the realm of biology, exploring **bio-computing** (the use of living systems to process information and solve design problems) and **bio-fabrication** (an expanded version of digital fabrication that adds layers of biological growth, assembly, and self-organization). In other words, the studio will explore new ways of using **biological systems as design tools**. Yet rather than identifying and using the **form of nature** for architectural design, we will identify and use the **logic of nature**.









6. LABORATORY EXPERIMENTS AND COMPUTER MODELS

Over the course of the semester, we will conduct **hands-on experiments** in the Brivanlou Lab at Rockefeller University, experiencing first-hand the process of collaborating with biological systems. We will collect data from these experiments and we will translate this data into rules, relationships, and **algorithms for design**. We will write scripts that generate complex forms based on changes in inputs and rules. This general approach reflects a relatively new paradigm in artificial intelligence: rather than program machines to follow fixed and known rules, set up an emergent system to evolve new and unexpected results. (No prior experience is necessary.)

With this process, we will **design at multiple scales simultaneously**—from DNA with a radius of about a billionth of a meter, to Earth with a circumference of about 40,000 meters—engaging 16 powers of ten in the same project.

7. HUMAN-CELL COLLABORATION

This studio will explore a **design ecosystem** where humans and biological cells cooperate to generate designs that a human alone—or nature alone—could never produce. This involves collaborating with biology rather imitating it.

This new design process may involve designing with unknowable forces, and designing dynamic relationships rather than designing fixed forms. These

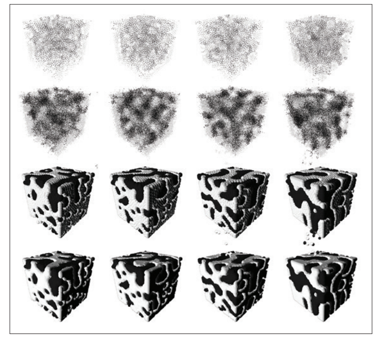
Images (top to bottom): Map of molecular pathways (Ali Brivanlou); Design of new ecosystem of bio fuel production and consumption (Nathan Smith, GSAPP Bio Oil Workshop); Diagram of living cells as factories; Use of quantum dots and 30 simultaneous microscopes to visualize neural communication in a transgenic tadpole (Ali Brivanlou).

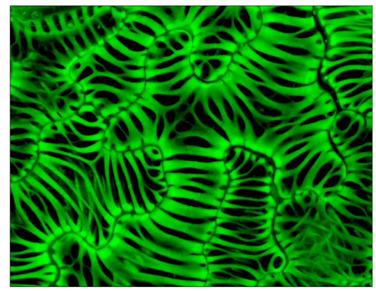
are huge transformations from the typical design process, but they are fitting for the dynamic and unstable world in which we now live. This human-cell cooperation represents a new paradigm for the Century of Biology and the future of architecture.

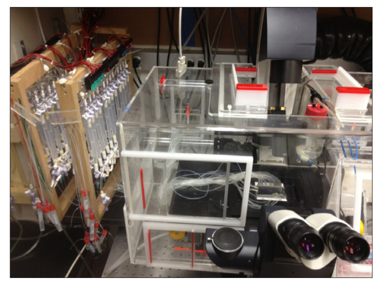
David Benjamin is Founding Principal of The Living, and Director of the Living Architecture Lab at Columbia University Graduate School of Architecture, Planning and Preservation. The firm and the lab create full-scale, functioning prototypes of the architecture of the future, and their work has won many awards including the Young Architects Prize from the Architectural League and the New Practices Award from the American Institute of Architects.

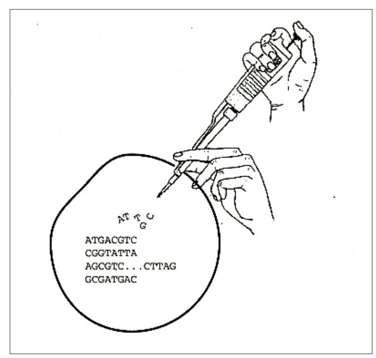
Ali Brivanlou is the Robert & Harriet Heilbrunn Professor, Head of the Laboratory of Molecular Embryology at Rockefeller University. He is a leader in the international effort to understand the intricacies of human stem cells and harness their therapeutic potential. He has played a key role in setting scientific standards for embryonic stem cell research and in defining which embryonic cells are true stem cells. His many honors include a Searle Scholar award, the McKnight scholar award, the John Merck award, a Klingenstein Fellowship, and a Presidential Early Career Award, the U.S. government's highest recognition for young scientists.

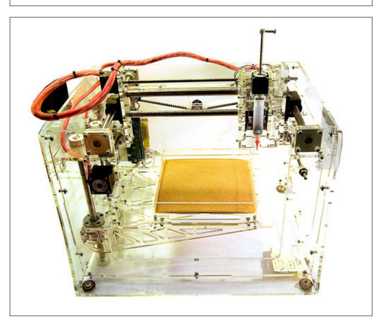
The studio is part of the **Advanced Data Visualization Project** (ADVP), sponsored by **Thomson Reuters**.











Images (top to bottom): Structures created through reaction diffusion behavior (Sydney Talcott, GSAPP Bio Design Studio 2013); Transgenic plant designed to induce growth of xylem cells in the leaves of arabidopsis plants, rather than in the stems of artichoke plants (Bio Logic, Fernan Federici and David Benjamin); Custom microfluidics and imaging machine (Ali Brivanlou Lab); Diagram of logic for a bio computing river (Mike Robitz, GSAPP Architecture Bio-Synthesis Seminar, 2010); 3D Bio Printer (Ginger Kreig Dosier); Tadpole embryos (Ali Brivanlou).