From the Quest for Fire to GATTACA: Systems and Synthetic Biology as the Next Wave of Technology Disruption in the Anthropocene

Dr. George Poste
Chief Scientist, Complex Adaptive Systems Initiative and Del E. Webb Chair in Health Innovation
Arizona State University
george.poste@asu.edu
www.casi.asu.edu

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The Journey to the Anthropocene: Mastery of Increasingly Sophisticated Intellectual Challenges and Technological Acceleration

First Communication Revolution 70K YBP

Agrarian Revolution 11K YBP

Scientific Revolution 0.5K YBP

Industrial Revolution 0.25K YBP

Digital Revolution 0.1K YBP

Molecular Biology Revolution 0.05K YBP
Understanding the Instructional Rules for Construction and Control of Complex Biological Systems

Exploring Biospace: Engineering Novel Biological Functions

Directed Evolution and Accelerated Evolution: From Individual Molecules to Organisms

Systems and Synthetic Biology as the Next Major Wave of Technological Disruption in the Anthropocene
Biological Diversity and Variation: “Endless Forms Most Beautiful”
“Endless Forms Most Beautiful”
Systems and Synthetic Biology and Exploring Biospace

Form and Function (diversity)

Instructional Information (code)

Systems Design (rule sets)

Design of Novel Biological Systems (exploring biospace)
“Endless Forms Most Beautiful”
Systems and Synthetic Biology and Exploring Biospace

**Form and Function**
- diversity (species)
- variety (individuals)
- specialization (cells)
- hierarchical integration (control systems)

**Instructional Information**
- code
- components
- assembly
- molecular signaling (information) modules and networks

**Evolution**
- fitness
- resilience
- adaption
- reproduction
- evolvability

**Complexity**
- emergence
- tipping points
- prediction of system behavior and risk of state shift
The Economy of Biological Organization: Defining the Common Building Components for Biological Systems and Combinatorial Assembly to Generate Functional Diversity

- **common genetic (digital) code in all life forms**
- **tool box of protein motifs for combinatorial assembly (“molecular lego”)**
- **assembly of structurally and functionally diverse proteins**
- **networks of protein interactions and complex molecular signaling patterns**

- **complex organism design**
- **stable networks and information fidelity (health)**
- **dysregulated networks and altered information patterns (disease)**
- **therapeutic modulation of perturbed networks**
Understanding the Rule Sets for Regulated Information Flow and Processing in Dynamic Biological Systems

“It”
(hardware/wetware)

“Bits”
(software and encoded design)

“Exploring Biospace”
(directed design of novel biological systems)
program and assemble new biological functions and organisms based on knowledge of the ‘rule sets’ underlying hierarchical biological systems

reprogramming existing biological signaling pathways and networks

expanding the dimension of explored biospace
  - design, simulation and construction of novel functions/organisms with no known natural evolutionary counter part
  - novel biotic: abiotic combinations

“directed evolution” and “accelerated evolution”
Advanced Manufacturing
Digital Programming of New 3-D Fabrication and Assembly Technologies
Programmable Matter: Computer-Controlled 3D Assembly of Structures of Increasing Complexity

- digital code for automated assembly of complex multi-scale structures
- uncoupling of design from fabrication and rise of point-of-need (PON) production capabilities
- 3D printing
  - spatio-temporal assembly at nano-/Ångstrom-level scale
  - abiotic materials
  - biotic materials
  - abiotic:biotic hybrids
- 4D systems
  - self-assembly, repair and reconfiguration
  - dynamic adaptive behavior: repair, reconfiguration
Digital Convergence

Natural Digital Software: DNA

Artificial Digital Software: Programming Languages

$3 - 4 \times 10^9$ years old

60 - 70 years old
Exploring Biospace
The Power of Combinatorial Interactions and Molecular Assembly

- Number of theoretical possibilities for synthetic assembly (biospace) far exceed narrow molecular space sampled in evolutionary time to date.
- Estimated 22,000 human genes.
- Two genes cooperate to create a function:
  \[ \frac{(22,000 \times 21,999)}{2} = 241,989,000 \text{ potential combinations} \]
- 100 genes generate a complex function:
  \[ 10^{65794} \text{ potential combinations} \]
Mapping the Coding Information for Organizational Complexity, Diversity and Variation in Biological Systems

- **rule sets**
  - organization of complex adaptive biological systems
- **fitness landscapes**
  - variation adaption evolution
- **exploring novel biospace**
  - biomimetic engineering and synthetic biology
- **biological novelty**
  - modification of organism performance and capabilities

- form and function
- instructional codes and information content
- mapping existing biospace
- dual use applications
- ethics, oversight and regulation
- augmentation (non-heritable)
- enhancement (heritable)
From Reactive Precarious Survival to Proactive Shaping of the Anthropocene

Technology Acceleration and Technology Convergence

Escalating Technical Complexity and Understanding Emergence in Complex Adaptive Systems
Complex Adaptive Systems: Increasing DDOF

- graded levels of autonomous behavior (components, system)
- escalating challenge of predicting system behavior and state shifts
“Oh, God help us! We’re in the hands of engineers.”

Dr. Ian Malcolm
‘Chaotician’: Jurassic Park