P.L.RAJ IAS & IPS ACADEMY

Building Bureaucrats Since 2006

6. Synthetic Biology – Science & Technology

Synthetic biology now allows scientists to design artificial life forms using AI and genetic engineering, creating major opportunities in medicine and industry while raising serious biosecurity, ethical, and environmental concerns. Recent breakthroughs demonstrate that a complete bacterial genome can be built chemically using a digital computer file — the world's first digitally created life. DNA sequencing costs have collapsed from $3 billion and ten years (Human Genome Project) to a few hundred dollars and a few hours in a small lab, democratizing genetic engineering at unprecedented scale and speed.

1. Recent Key Findings

The Complexity Paradox

1. Genetic tests showing how complex a living creature looks does NOT depend on total gene count
2. **Single-celled bacterium-** ~4,300 genes
3. **Human being-** ~22,000 protein-coding genes
4. **Water flea (Daphnia)-** 31,000 genes — far more than humans
5. Biological complexity driven by gene regulation, NOT gene count

Cheaper and Faster Technology

1. DNA sequencing speed growing exponentially while cost collapsed completely
2. **Earlier-** International team, 10+ years, $3 billion (Human Genome Project)
3. **Now-** Few hours, few hundred dollars, small lab
4. Democratizing genetic research globally

Computer-Made Life

1. Scientists proved complete bacterial genome can be built chemically using digital computer file
2. Man-made DNA successfully placed inside living cell with natural DNA removed
3. **Result-** World's first digitally created life
4. Landmark proving biology can be treated as programmable system

2. About Synthetic Biology

Definition

1. Field applying engineering rules to biology to design, build new biological parts, tools, systems
2. Treats living organisms as programmable machines

Two Main Methods

Top-Down Synthetic Biology (Genome Replacement)-

1. Takes existing living cell
2. Completely replaces natural DNA with human-designed, chemically made DNA chains
3. Changes how cell behaves or what it produces
4. Example- Creating first synthetic bacterial cell

Bottom-Up Synthetic Biology (Protocells)-

1. Does NOT use any pre-existing life
2. Scientists build simple cell completely from scratch using non-living chemistry
3. **Protocells-** Using fatty-acid vesicles (tiny fat bubbles) naturally forming closed walls
4. These vesicles trap RNA inside, copy genetic material under right conditions, split into two
5. Mimicking earliest stages of life's origin

3. Core Genetics vs. Biological Complexity

DNA — Basic Code of Life

1. Deoxyribonucleic acid (DNA)- Main building block of genome
2. Four-letter chemical alphabet-
    1. **A** — Adenine
    2. **T** — Thymine
    3. **G** — Guanine
    4. **C** — Cytosine
3. Sequences of these letters encoding all biological information

The Role of Transcription Factors

1. True biological complexity driven by gene control rather than total gene numbers
2. Regulatory regions of DNA acting like light switches
3. **Transcription factors-** Control proteins attaching to regulatory regions turning specific genes "on" or "off"
4. This interaction deciding-
    1. How much protein is made
    2. When protein is produced
    3. Where in the body it is expressed
    4. Duration of expression
5. Explains why humans (22,000 genes) are more complex than water fleas (31,000 genes)

4. Significance of Synthetic Biology

Improving Healthcare

1. Advanced gene design allowing scientists to build special cell factories
2. Manufacturing targeted medicines, new vaccines
3. Treatments for severe inherited conditions like Phenylketonuria (PKU — metabolic disorder)
4. Personalized medicine, cancer immunotherapy applications
5. Faster vaccine development (COVID-19 mRNA vaccine precedent)

Cleaning the Environment and Clean Energy

1. Artificial cells designed to-
    1. Trap carbon (climate change mitigation)
    2. Clean up toxic industrial chemical spills (bioremediation)
    3. Produce clean biofuels directly from non-food plants
2. Reducing dependence on fossil fuels
3. Addressing industrial pollution

Mapping the Tree of Life

1. Genome sequences acting like detailed history book of Earth
2. Showing how different animals, plants are related
3. How evolutionary branches split, how living things change through mutations
4. Filling gaps where fossils are missing
5. Understanding human origins, migration, disease evolution

Other Applications

1. **Agriculture-** Drought-resistant, pest-resistant crops; nitrogen-fixing plants reducing fertilizer dependence
2. **Materials-** Spider silk proteins, biodegradable plastics, novel biomaterials

3. **Biosensors-** Detecting pollutants, pathogens, explosives using engineered organisms
4. **Food security-** Lab-grown meat, precision fermentation, engineered food crops

6. Concerns That Need to Be Tackled

The Risk of Independent Copying

1. Unlike machines or nuclear plants, engineered biological creatures can convert digital data into self-replicating products
2. Once let into nature, they breed independently
3. Making them nearly impossible to bring back or control
4. Containment failure = permanent ecological change

The Evolution Trap

1. Artificial life forms released into nature will naturally mix with wild plants, animals
2. Over time undergo unmonitored mutations driven by natural selection
3. Can harm local wildlife, damage ecosystem balances in unpredictable ways
4. Gene drives (spreading engineered traits through wild populations) particularly concerning

Biosecurity and Dual-Use Risks

1. Gene-making becoming cheap, easy + AI power = higher risk of-
    1. Accidental lab leaks
    2. Intentional creation of highly dangerous, custom-made germs (bioweapons)
2. Dual-use dilemma- Same knowledge enabling vaccines also enabling bioweapons
3. Low-cost barrier to entry increasing non-state actor risk

Ethical Concerns

1. "Playing God" — creating, designing life forms raises profound philosophical, religious questions
2. Intellectual property over life forms
3. Access equity- Who benefits from synthetic biology breakthroughs (rich vs. poor nations)
4. Consent issues in human genetic applications
5. Long-term ecological consequences unknown

Regulatory Gaps

1. Existing biosafety laws designed for earlier era of slower, expensive biotechnology
2. Struggling to keep pace with rapid, cheap AI-driven gene design
3. International regulatory coordination insufficient

7. Way Forward

Flexible Rules and Oversight

1. Governments moving away from old, slow safety laws
2. Fast, smart safety checks keeping pace with quick breakthroughs in gene design, AI
3. Adaptive regulatory frameworks updating continuously
4. Pre-market risk assessment for synthetic organisms

International Biosecurity Agreements

1. Biological germs not respecting national borders
2. Global agreements, treaties urgently needed-
    1. Monitor commercial DNA orders
    2. Stop illegal creation of dangerous germs
    3. Strengthen Biological Weapons Convention (BWC) enforcement
    4. International synthetic biology registry

Safe Isolation Practices

1. First real-world uses strictly locked inside closed industrial tanks
2. Any artificial life meant for outside use must have-
    1. Built-in genetic kill-switches stopping breeding outside laboratory
    2. Multiple containment layers
    3. Regular monitoring, reporting requirements

Ethical Governance

1. Inclusive global dialogue involving scientists, ethicists, civil society, governments
2. Benefit-sharing mechanisms ensuring Global South access
3. Moratorium on most dangerous applications pending framework development

8. Conclusion

Synthetic biology's convergence with AI represents both transformative opportunity and existential risk requiring urgent global governance frameworks balancing innovation with biosecurity, ethics, and ecological protection.

Source- **https-//www.thehindu.com/sci-tech/science/genie-synthetic-biology-out-power-and-peril/article71041355.ece**