



# The International Institute for Applied Systems Analysis

166.716 Basics of process development and life cycle assessment

Fabian Schipfer – Technology assessment and systems engineering

18.12.2025

# Chapter 1 – Technology assessment and forecasting

1. Pre-1900 Technology Assessment Roots
2. Technology assessment – early foundations (1900 ..)
3. Technology assessment in the war and inter-war periods (1914 – 1945)
4. Institutionalization of Technology Assessment (1960s–1970s)
5. Forecasting & Foresight (1970s–1990s)
6. Modern TA & Sustainability Integration (1990s–present)
7. Some thoughts (2020s – 2040s+)

# Pre-1900 Technology Assessment Roots

**Context:** Steam engines, mechanized textile production, railroads, and coal-based energy transformed economies and societies.

## Adam Smith (1723–1790)

Political economist

*Wealth of nations* (1776)

- Technology as driver of progress
- Division of labor & efficiencies
- Economic gain as incentive for innovation
- By combining diverse knowledge
- Mental mutilation through specialization
- Society must manage impacts, ensuring broad societal good beyond just producer gain

## Friedrich Engels (1820–1895)

Philosopher, sociologist, economist

*The Condition of the Working Class in England* (1845)

- Technology intrinsically linked to human development
- Creating new social conditions both
  - Positive (solve problems)
  - Negative (worker exploitation)
- Key to understand historical change
- “Dialectical materialism”
- making workers appendages to machines
- need to anticipate future tech

## Karl Marx (1818–1883)

Philosopher

*Capital* (1867)

*Machinery & Modern Industry*

- Technology as non-neutral force within capitalism
- Driving economic development, but controlled by capital for profit
- Separation of workers from the product, process, and their own potentials
- Reducing reliance on skilled labor, creates unemployment
- Boosts productivity but deepens inequality > leading to revolution

# Pre-1900 Technology Assessment Roots

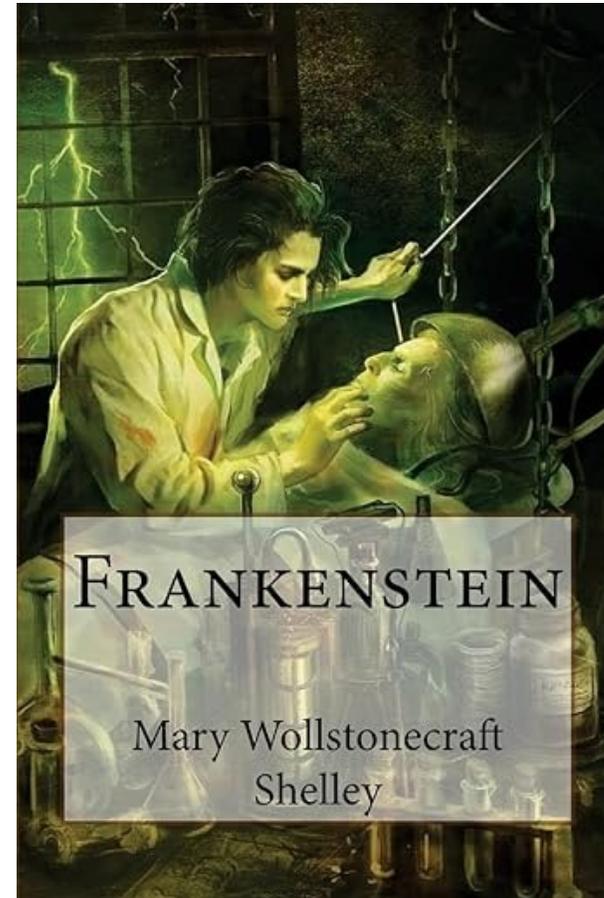
**Context:** Steam engines, mechanized textile production, railroads, and coal-based energy transformed economies and societies.

## Mary Shelley (1797–1851)

Novelist (Mother of Sci-Fi)

*Frankenstein (1818)*

- Mastery over natural processes
- Who is responsible for the outcomes of technological creation?
- Emergent properties and unintended consequences
- Human dimension as antidote; empathy and social integration



# Technology assessment – early foundations (1900 ..)

**Context:** Electrification, assembly lines, chemical industries, and early automation reshaped production and urban life.

## **Thorstein Veblen (1857–1929)**

Political economist and sociologist

*The Engineers and the Price System (1921)*

- Critique of industrial capitalism and its inefficiencies
- Advocated for engineers as rational planners over profit-driven managers → **technocracy movement**
- Technology should serve social welfare, not speculative finance
- Warned against “business sabotage” of technological potential (e.g. planned obsolescence, artificial scarcity)

## **Frederick Winslow Taylor (1856–1915)**

Mechanical engineer

*The Principles of Scientific Management (1911)*

- Introduced scientific management for efficiency → **decision theory**
- Technology as a tool for productivity optimization
- Emphasized time-motion studies and standardization → Taylorism
- Criticized for reducing worker autonomy and creativity

## **Lewis Mumford (1895–1990)**

Historian and philosopher of technology

*Technics and Civilization (1934)*

- Technology (beginning with the clock) as a cultural force, not just mechanical progress
- Distinguished “polytechnic” (life-enhancing) vs. “monotechnic” (dominating) technologies
- Warned against authoritarian tendencies in large-scale systems
- Advocated for **human-centered technological development**

# Technology assessment – early foundations (1900 ..)

**Context:** Electrification, assembly lines, chemical industries, and early automation reshaped production and urban life.

## Joseph Schumpeter (1883–1950)

Economist

*The Theory of Economic Development*  
(1911)

- Innovation as “creative destruction” driving economic cycles
- Technology as a disruptive force reshaping markets
- Entrepreneur as key agent of technological change
- Highlighted S-curves and substitution dynamics

## Beatrice Webb (1858–1943)

Social reformer and economist

*Industrial Democracy* (1897)

- Together with Sidney Webb (Fabian Society)
- Studied impacts of industrial organization on labor
- Pioneering social research and policymaking
- Advocated for cooperative models and social planning
- Technology must align with democratic governance
- Critiqued laissez-faire industrialization

## Rabindranath Tagore (1861–1941)

Poet, philosopher, social thinker

*The Religion of Man* (1931)

- One of the first non-European Nobel Prize winners
- Critiqued industrial modernity as culturally alienating
- Warned against blind imitation of Western technological progress
- Advocated for harmony between technology and human values
- Emphasized spiritual and ecological dimensions of development

# Technology assessment in the war and inter-war periods (1914 – 1945)

**Context:** Electrification, mass production, chemical industries, and early automation accelerated industrial growth; World Wars drove military innovation; holocausts; atomic bomb; onset of nuclear energy and aerospace technologies marking the dawn of the atomic age and Cold War techno-politics.

## Jacques Ellul (1912–1994)

Sociologist and philosopher

*The Technological Society* (1954)

- Technology as autonomous and self-accelerating
- **Technique is ultimately focused on the concept of efficiency**
- Warned against technological determinism
- Critiqued illusion of neutrality in technical progress
- Advocated for ethical and democratic control of technology

## Martin Heidegger (1889–1976)

Philosopher

*The Question Concerning Technology* (1954)

- Technology as a mode of revealing, not mere tools
- “Enframing” (Gestell): technology orders reality
- **Danger of reducing nature and humans to resources**
- Called for meditative thinking beyond technical rationality

## Leo J. Kranzberg (1912–1995)

Historian of technology

*Technology and History: Kranzberg’s Laws* (1986)

- **Technology is neither good nor bad; nor is it neutral**
- Impacts depend on context and societal choices
- Technology creates new problems alongside solutions
- Advocated for historical perspective in technology policy

# Institutionalization of Technology Assessment (1960s–1970s)

**Context:** Post-war technological optimism, rapid industrial growth, nuclear energy expansion, aerospace programs, and early environmental awareness drove governments to formalize technology assessment as a policy tool, student protests, civil rights movements, anti-war activism, international multilateral organizations

## Alvin Weinberg (1915–2006)

Physicist and science policy advocate  
*Science and Trans-Science (1972)*

- Introduced concept of “trans-scientific” questions beyond pure science
- Advocated for societal oversight of large-scale technologies (big science)
- Highlighted ethical and political dimensions of nuclear energy
- Called for institutionalized technology assessment

## Rachel Carson (1907–1964)

Marine biologist and environmentalist  
*Silent Spring (1962)*

- Exposed ecological and health risks of chemical pesticides
- Critiqued technological optimism in agriculture
- Advocated for precautionary principle in technology use
- Sparked modern environmental movement and policy reforms

## Ivan Illich (1926–2002)

Social critic and philosopher  
*Tools for Conviviality (1973)*

- Critiqued industrial systems for eroding autonomy and community
- Advocated for “convivial tools” enabling human-scale technology  
→ degrowth & appropriate tech
- Warned against over-professionalization and dependency on complex systems
- Linked technology design to social justice and empowerment

# Forecasting & Foresight (1970s–1990s)

**Context:** Oil crises, space race, and global competition spurred scenario planning, Delphi methods, and technology forecasting for strategic decision-making.

## Herman Kahn (1922–1983)

Futurist and strategist

*The Year 2000: A Framework for Speculation on the Next Thirty-Three Years* (1967)

- Pioneered scenario planning for long-term technological futures
- **Emphasized probabilistic thinking in forecasting**
- Linked technology foresight to national security and policy
- Criticized for techno-optimism and neglect of social risks

## Everett Rogers (1931–2004)

Communication scholar

*Diffusion of Innovations* (1962)

- Developed adopter categories (innovators, early adopters, etc.)
- **Explained social dynamics of technology diffusion**
- Highlighted role of communication channels in adoption
- Applied theory to agriculture, health, and ICT

# Modern TA & Sustainability Integration (1990s–present)

**Context:** Oil crises, space race, and global competition spurred scenario planning, Delphi methods, and technology forecasting for strategic decision-making.

## **Masahiro Mori (1927– )**

Robotics researcher

*The Uncanny Valley (1970)*

- Explored human-technology interaction in robotics
- Identified psychological thresholds in design acceptance
- Influenced human-centered design principles
- Bridging engineering and cognitive science

## **Ruth Schwartz Cowan (1941– )**

Historian of technology

*More Work for Mother (1983)*

- Studied household technologies and gender roles
- Technology reshapes domestic labor, not always reducing it
- Criticizes assumptions of progress and convenience
- Highlighting social dimensions of technological adoption

## **Lotte Bailyn (1930– )**

Organizational theorist

*Living with Technology: Issues at Mid-Career (1980)*

- Studied organizational and social impacts of technological change
- Highlighted how technology reshapes work-life balance and career trajectories
- Advocating for gender-sensitive approaches in workplace technology adoption
- Emphasizing human factors and participatory design in technology assessment

# Modern TA & Sustainability Integration (1990s–present)

**Context:** Globalization, digitalization, climate change awareness, and sustainability agendas reshaped technology assessment. Focus broadening to social, ethical, and environmental dimensions, integrating participatory approaches and governance frameworks

## Armin Grunwald (1957– )

Philosopher and technology assessment scholar

*Technology Assessment: Concepts and Methods* (2018)

- Advocating for integrative TA combining ethics, policy, and systems thinking
- Emphasizing **participatory approaches** and stakeholder involvement
- Linking TA to sustainability and responsible innovation
- Criticizing reductionist views of technology impacts

## Helga Nowotny (1937– )

Science and technology studies scholar  
*Uncertainty in Science and Society* (2003)

- Technology embedded in social and cultural contexts
- Emphasizes uncertainty and reflexivity in innovation
- Uncertainty as a motor for positive change
- Industrial revolution had enormous unintended consequences → invention of institutions
- People started **confusing risk with danger, still lasts until today**

## Sheila Jasanoff (1944– )

Science and technology policy scholar  
*Designs on Nature* (2005)

- Developed concept of **“co-production” of science and social order**
- Studied governance of emerging technologies (biotech, climate)
- Emphasized cultural and institutional contexts of technology assessment
- Advocated for anticipatory governance and ethical foresight
- [2022 Holbert Price](#)

# Thoughts on uncertainty

## Helga Nowotny (1937– )

Science and technology studies scholar  
Uncertainty in Science and Society  
(2003)

- Technology embedded in social and cultural contexts
- Emphasizes uncertainty and reflexivity in innovation
- Uncertainty as a motor for positive change
- Industrial revolution had enormous unintended consequences → invention of institutions
- People started **confusing risk with danger, still lasts until today**

- Uncertainty is difficult to talk about and even more difficult to quantify and model
- But the essence of
  - everybody's mundane decisions
  - political tendencies and party programs
  - long-term political cycles  
more progressive – conservative – regressive ...
  - technology assessment work
  - ....
- Humanity is anticipating and planning for a growing portfolio of uncertainties
- Let's start talking about risk again having potential for gain AND loss (think about casino gambling). That's also according to ISO on Risk Management
- Technology shifts ↔ Social order shifts  
Industrial revolution ↔ national institutions  
Industrialization & global supply ↔ international institutions  
Internet, clean tech, AI ↔ ?? Current and future orders ??

# Some thoughts (2020s – 2040s+)

## **Electrotechnical engineering**

- PV- & wind & tidal
- Electrification of everything
- Batteries
- Quantum computing

## **Software engineering**

- AI & machine learning
- Cyber-physical systems
- Digital twinning
- Cybersecurity

## **Mechanical engineering**

- Advanced manufacturing
- Robotics & automation
- Materials & structures
- Mobility

## **Chemical engineering**

- Green chemistry
- Biochemical & Bioengineering
- ChatGPT moment for CRISPR
- Modular, distributed chemical plants

## **Co-production of science and social order:**

- More appropriate and human centered sizes of industries
- “Inadvertent” climate progress starting from the global south
- AI boom and bust cycles shifting attention to real societal value
- Global missions translations to local goals, capacities, cultures
- Converging sustainability, safety, security, resilience agendas

# Chapter 2 – Innovation, technology development & diffusion

1. Innovation and Diffusion Theories
2. Technology Readiness and Lifecycle Thinking
3. Socio-Technical Transition and Multi-Level Perspective
4. Contemporary pathways and Systemic Innovation

# Innovation and diffusion theories



Joseph Schumpeter  
(1883 – 1950)



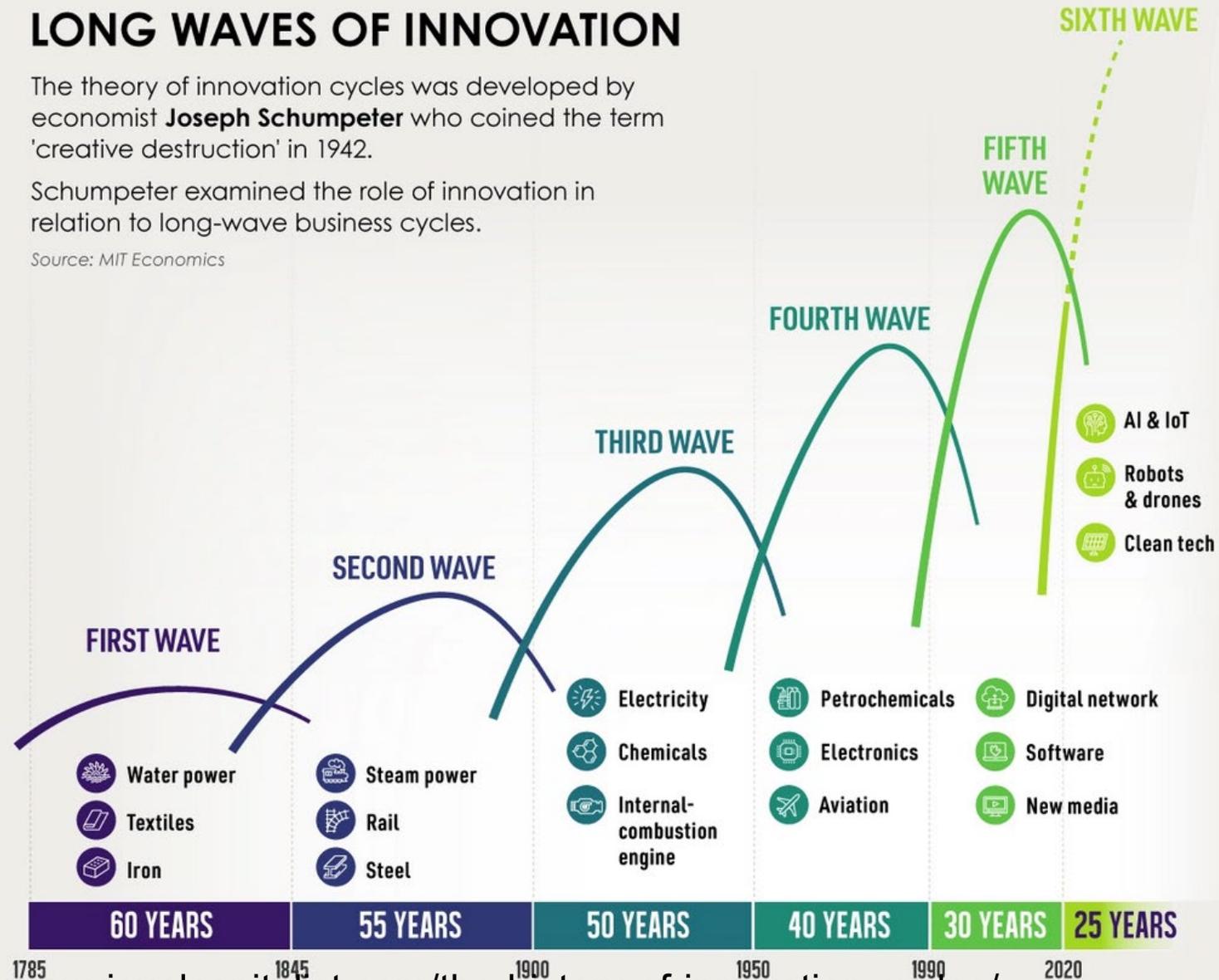
Nikolai  
Kondratjew  
(1892 – 1938)

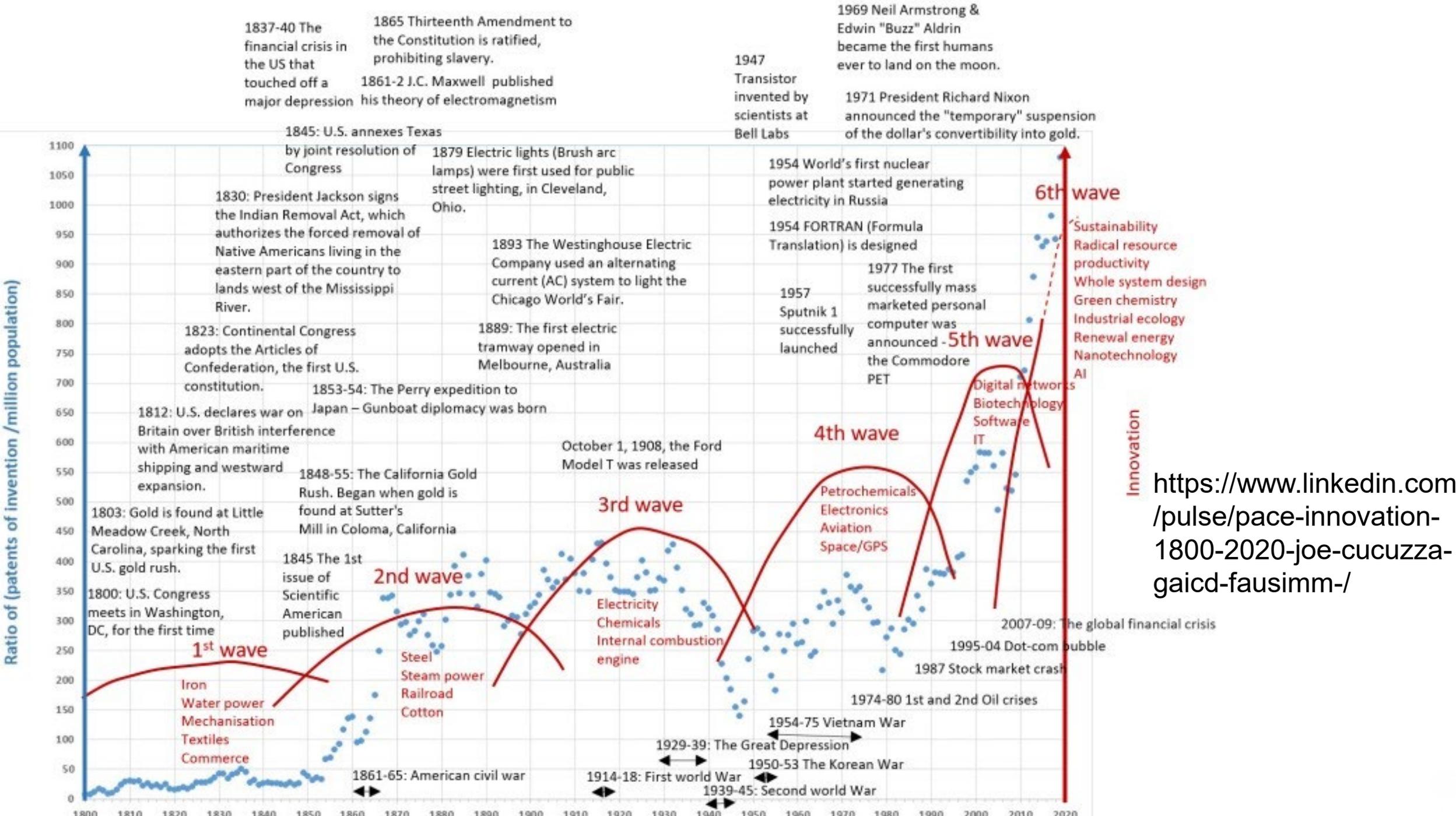
## LONG WAVES OF INNOVATION

The theory of innovation cycles was developed by economist **Joseph Schumpeter** who coined the term 'creative destruction' in 1942.

Schumpeter examined the role of innovation in relation to long-wave business cycles.

Source: MIT Economics

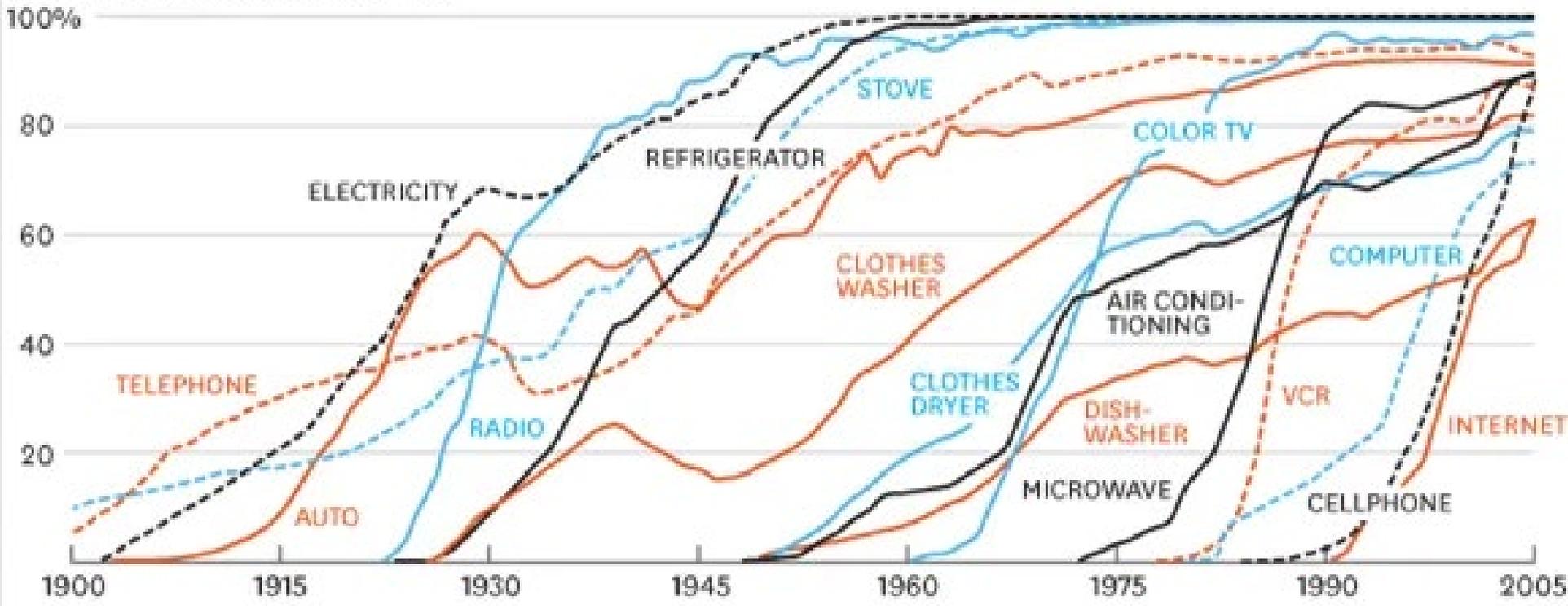




<https://www.linkedin.com/pulse/pace-innovation-1800-2020-joe-cuczuzza-gaicd-fausimm/>

# CONSUMPTION SPREADS FASTER TODAY

PERCENT OF U.S. HOUSEHOLDS



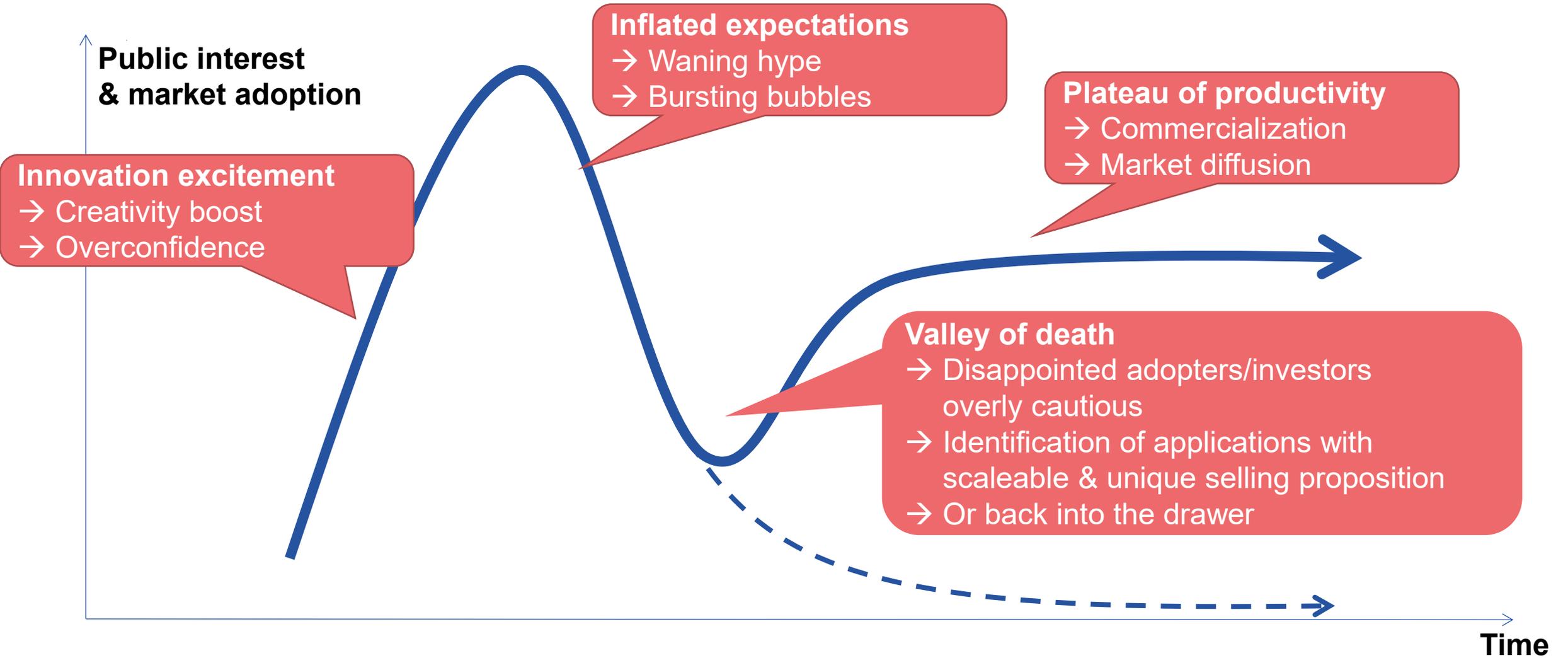
SOURCE MICHAEL FELTON, THE NEW YORK TIMES

STRATEGIC HBR.ORG

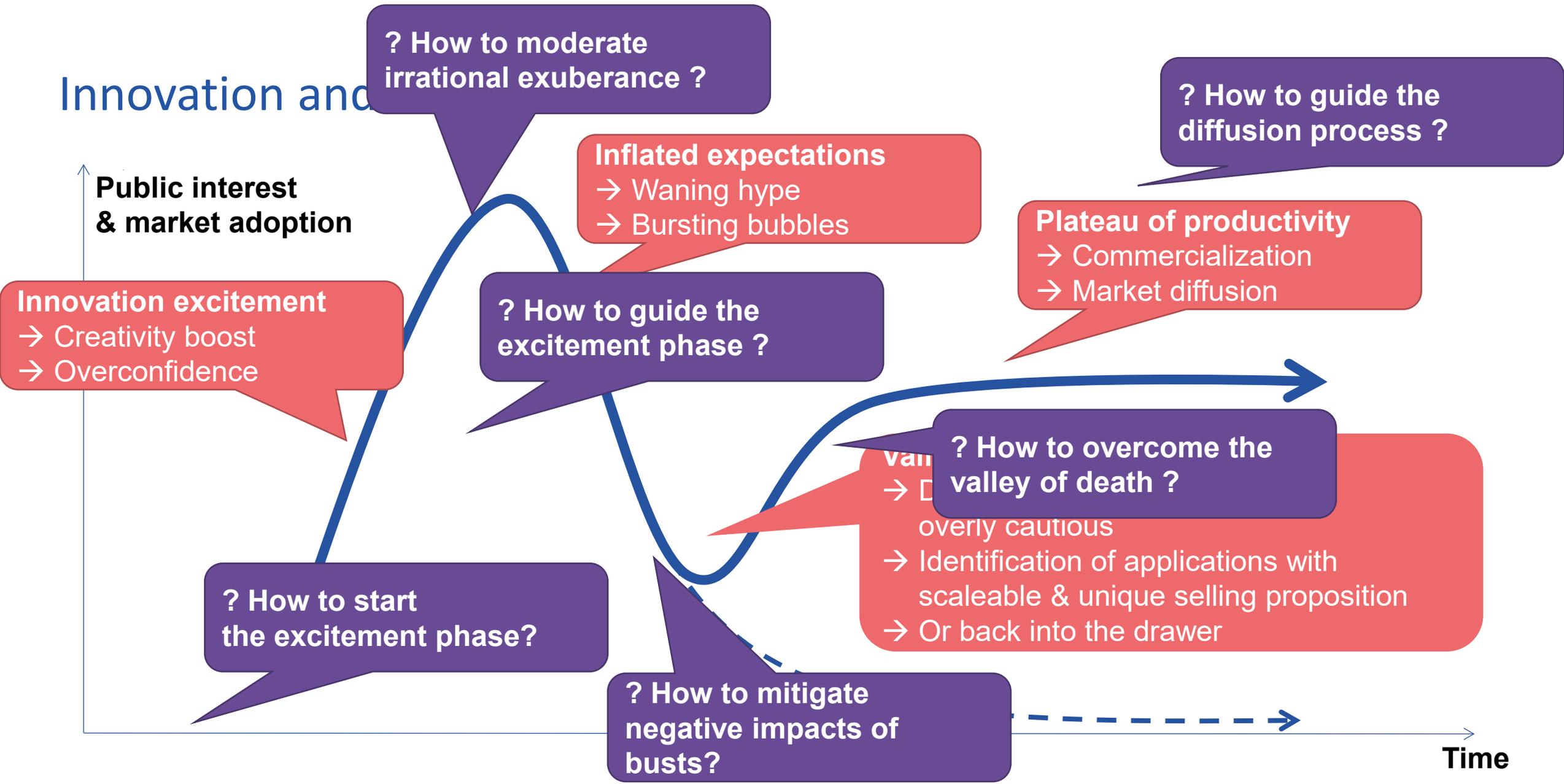
# Innovation and diffusion theories

1. How fast is the rate of diffusion ?
2. What slows down diffusion, what accelerates it ?
3. What is the theoretical diffusion ceiling – every household, person, device, ... ?
4. What is the role of human networks, distances and spatial context in diffusion ?
  - Gabriel Tarde
  - Hägerstrand et al. (1968)
  - Yuriy Davidovich Schmidt

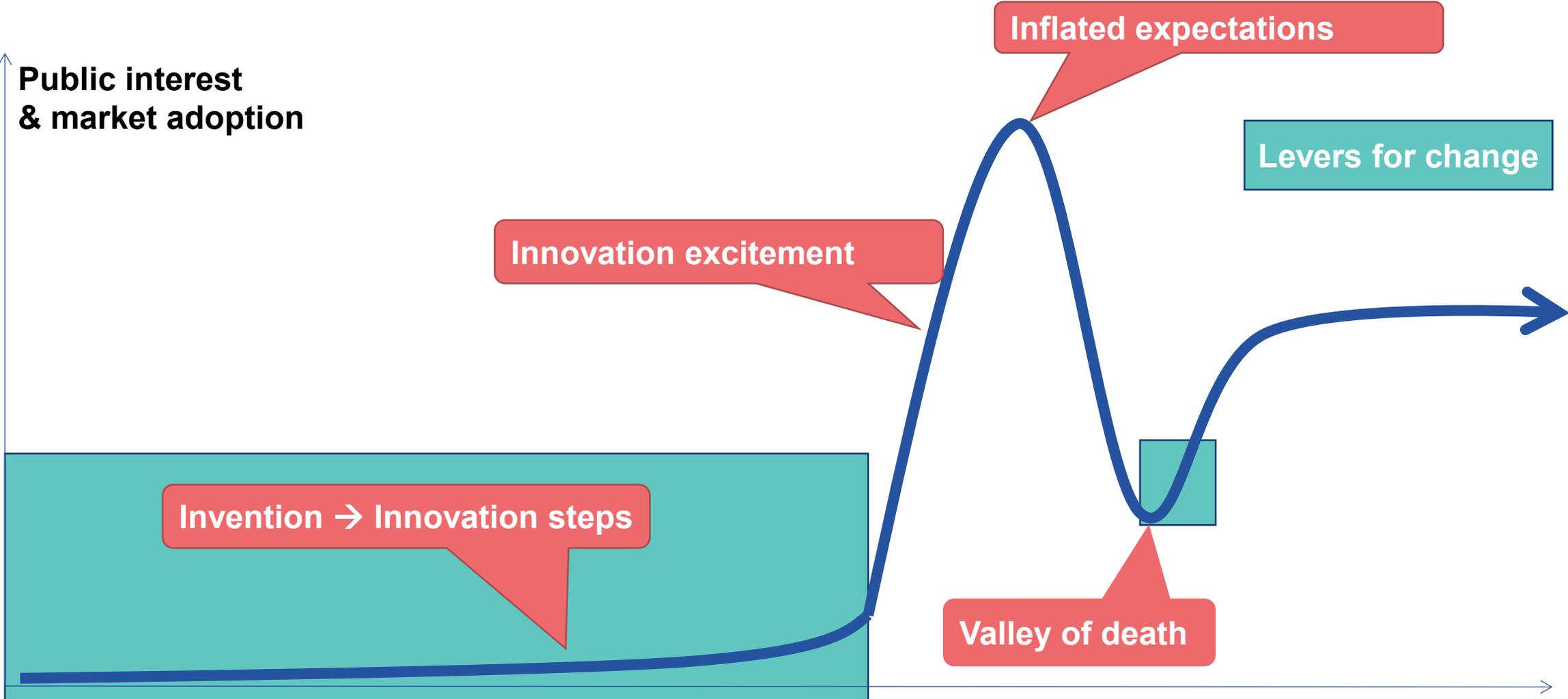
# Innovation and diffusion theories



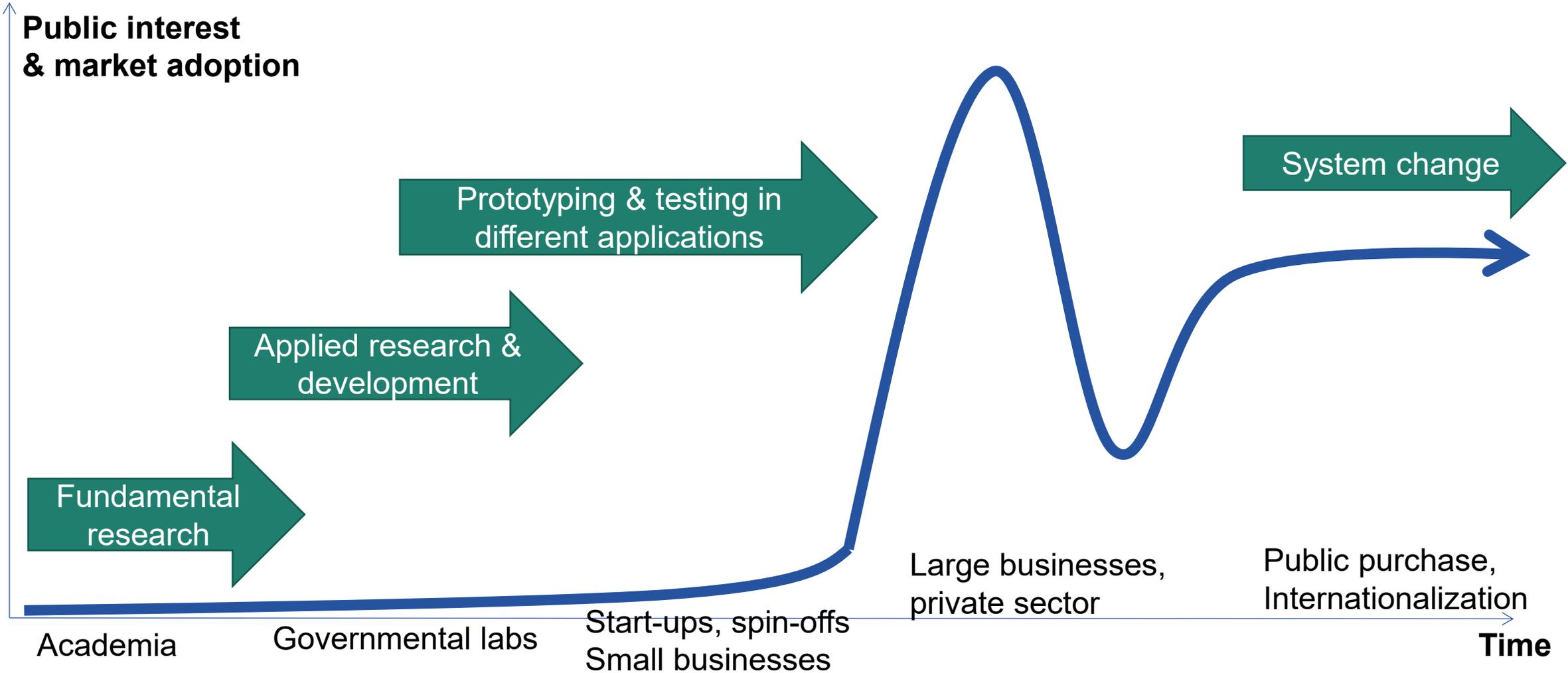
# Innovation and



# Innovation and diffusion theories

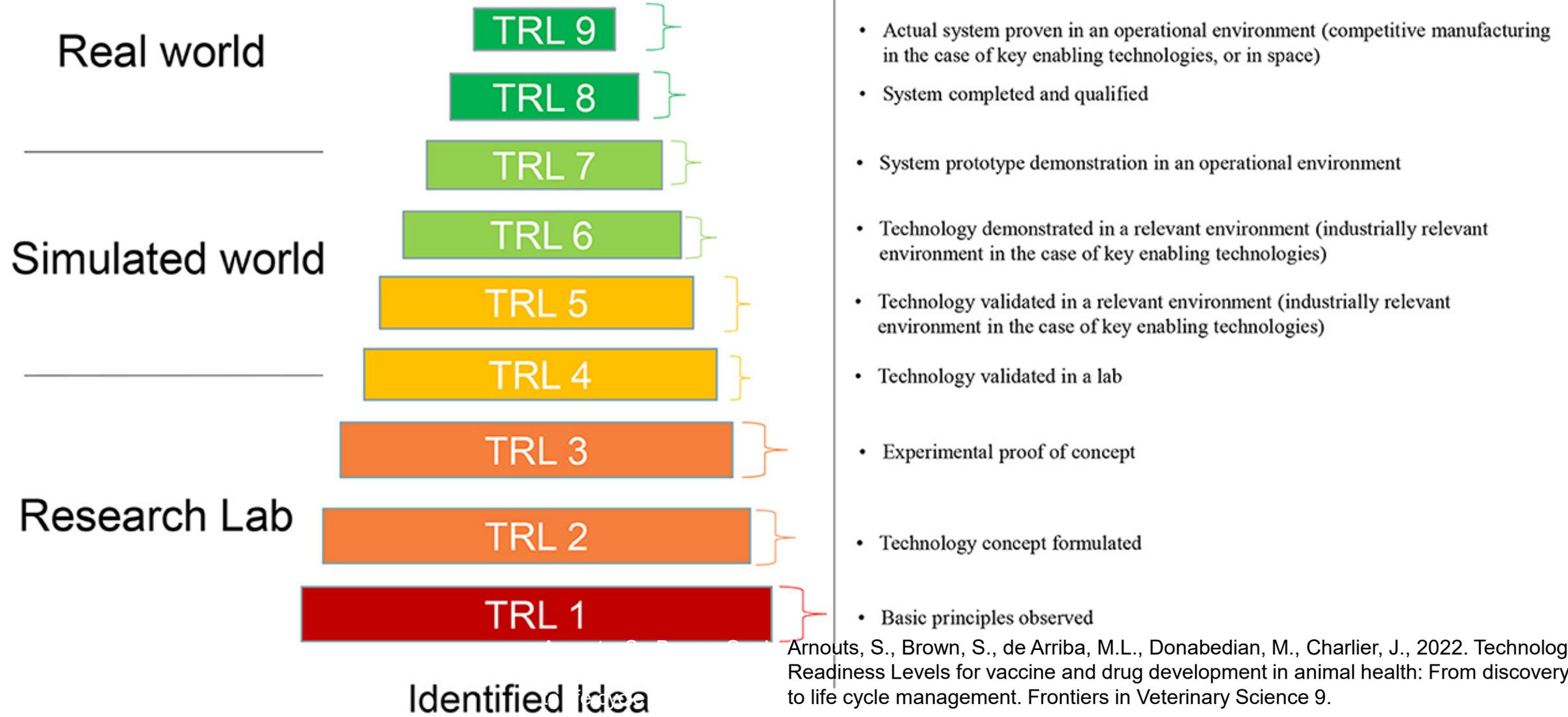


# Innovation and diffusion theories



# Technology Readiness and Lifecycle Thinking

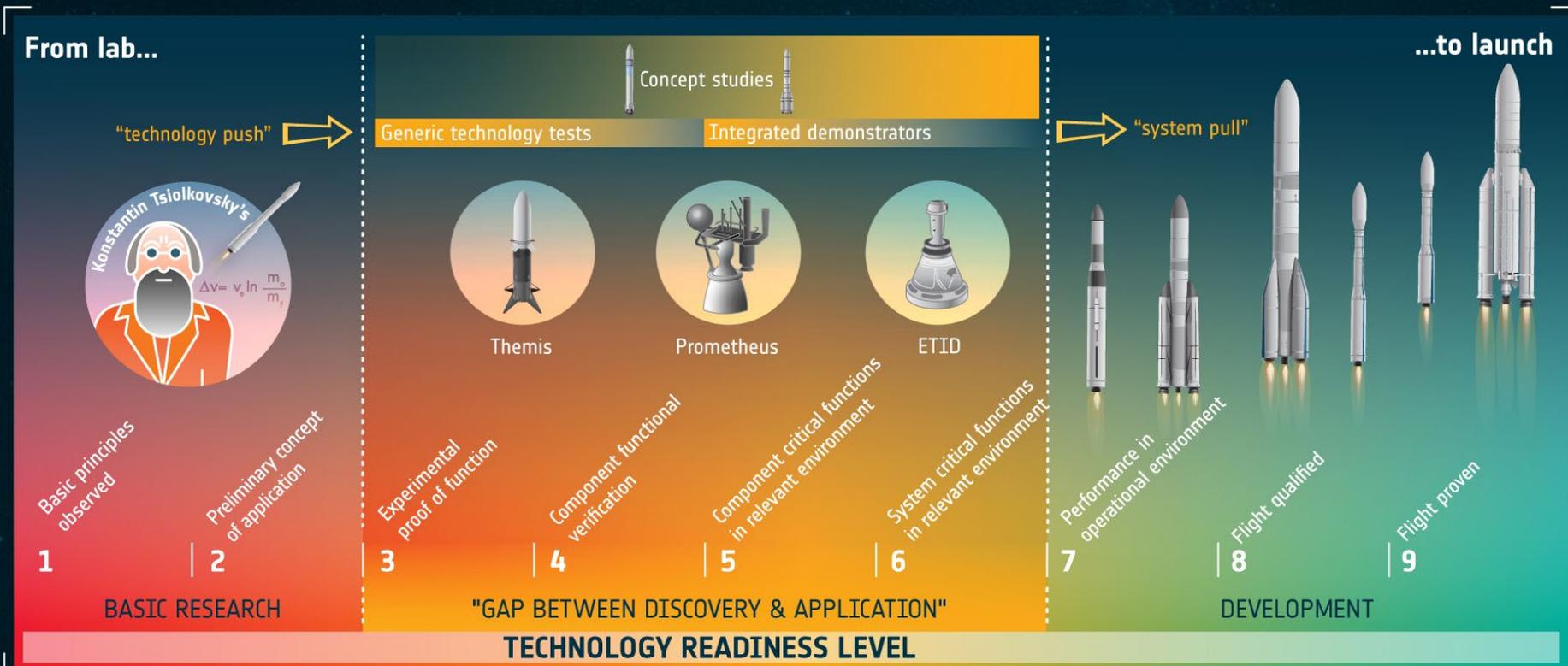
Commercial deployment



# Technology Readiness and Lifecycle Thinking

Unit scaling

## → FUTURE LAUNCHERS PREPARATORY PROGRAMME

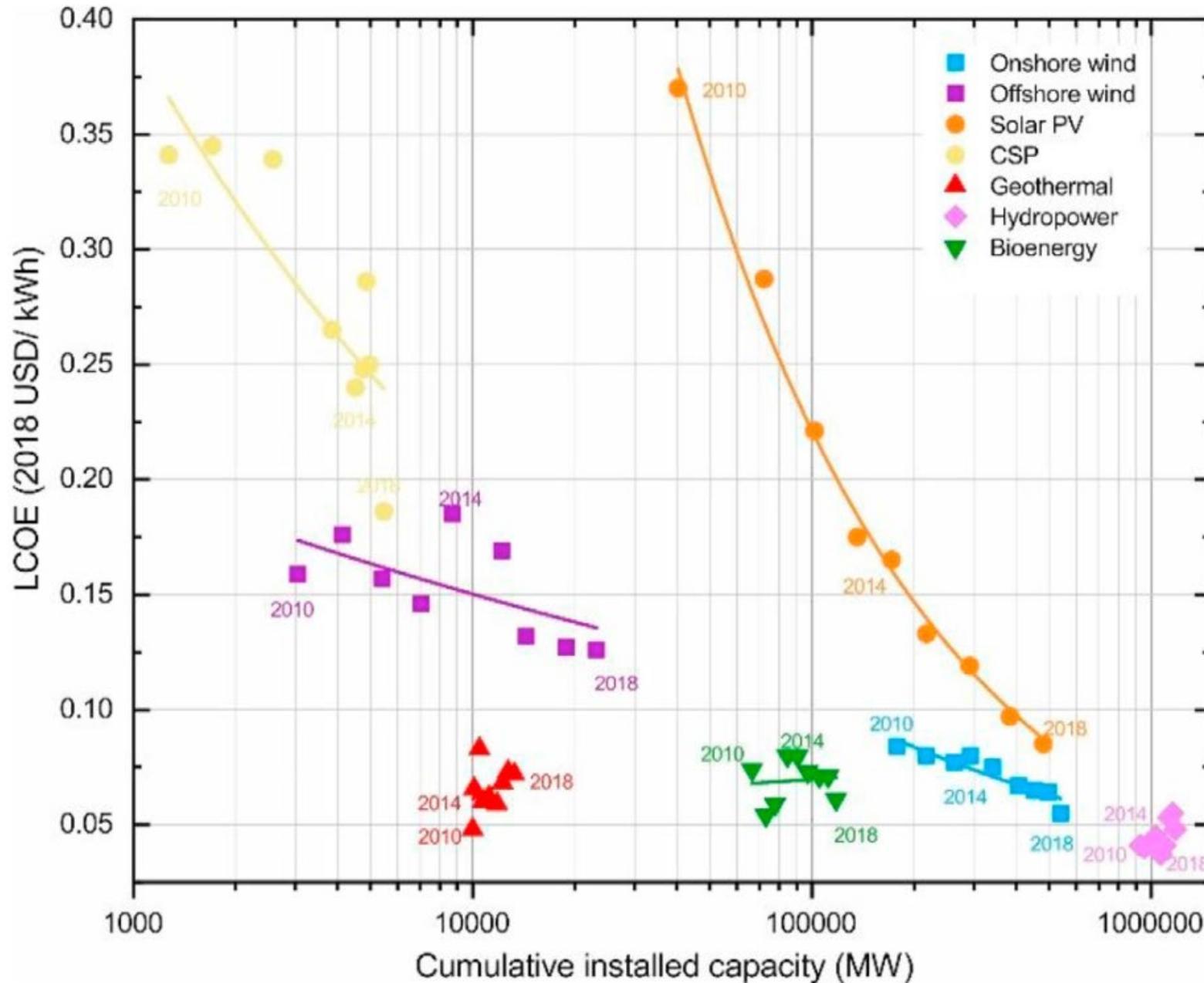


#Space19plus



# Capacity scaling

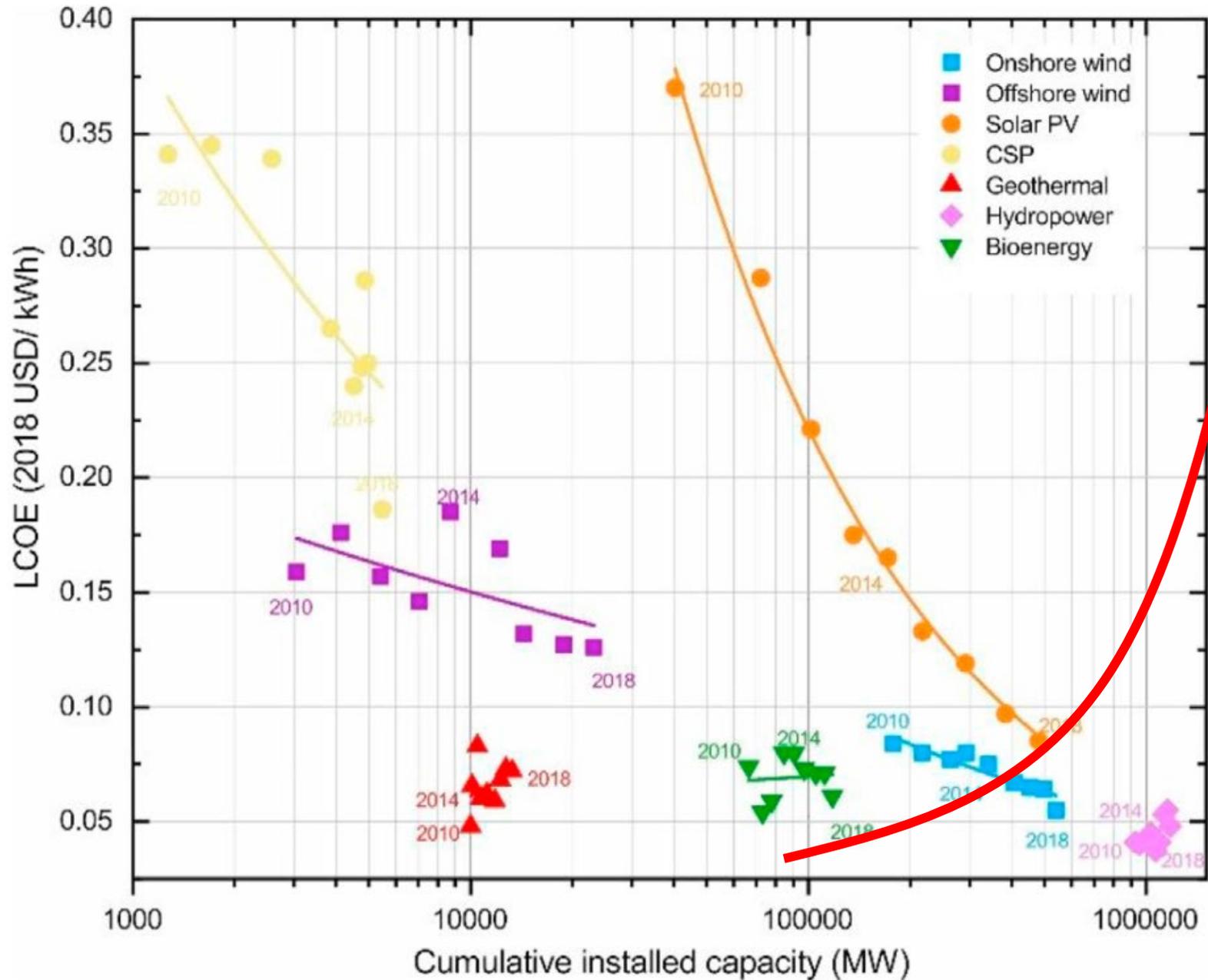
1. Technological & organizational learning → specific costs of application decrease



Yao, Y., Xu, J.-H., Sun, D.-Q., 2021. Untangling global levelised cost of electricity based on multi-factor learning curve for renewable energy: Wind, solar, geothermal, hydropower and bioenergy. *Journal of Cleaner Production* 285, 124827.

<https://doi.org/10.1016/j.jclepro.2020.124827>

**Fig. 3.** One-factor learning curve based on cumulative installed capacity fitting result.



## Capacity scaling

1. Technological & organizational learning → specific costs of application decrease
2. Impact on a landscape level (social & environmental) increase for both
  - beneficial consequences
  - detrimental consequences

Impacts (+ and -)

Yao, Y., Xu, J.-H., Sun, D.-Q., 2021. Untangling global levelised cost of electricity based on multi-factor learning curve for renewable energy: Wind, solar, geothermal, hydropower and bioenergy. *Journal of Cleaner Production* 285, 124827. <https://doi.org/10.1016/j.jclepro.2020.124827>

**Fig. 3.** One-factor learning curve based on cumulative installed capacity fitting result.

# Socio-technical transitions and multi-level perspective

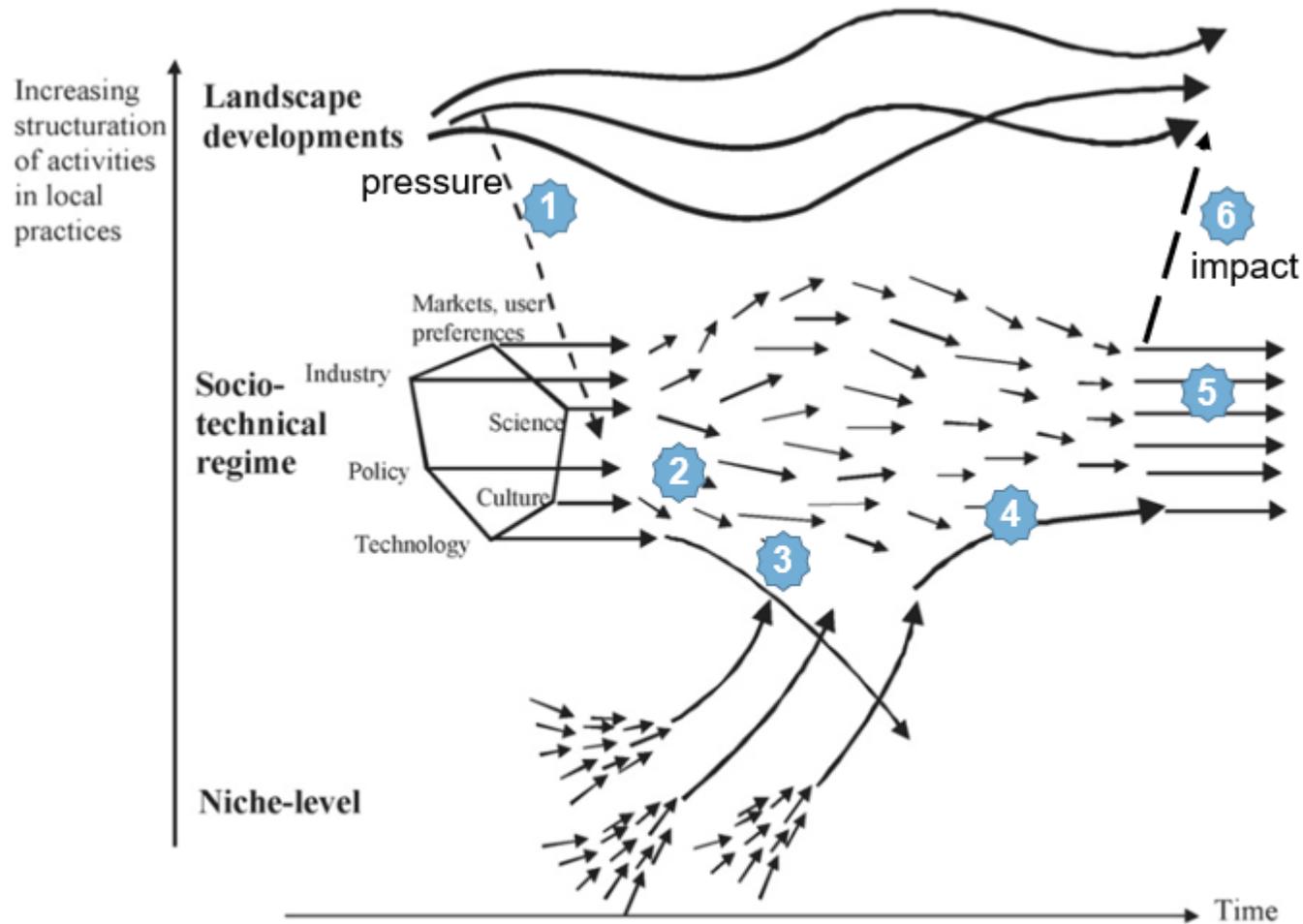


Fig. 6. De-alignment and re-alignment pathway.

1. Landscape pressure (social or environmental)
2. Destabilizing incumbent regime
3. Window of opportunities for innovations
4. Adoption & stabilization of innovations
5. Formation of new regime
6. Regime impacting on landscape

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. *Research Policy* 36, 399–417. <https://doi.org/10.1016/j.respol.2007.01.003>

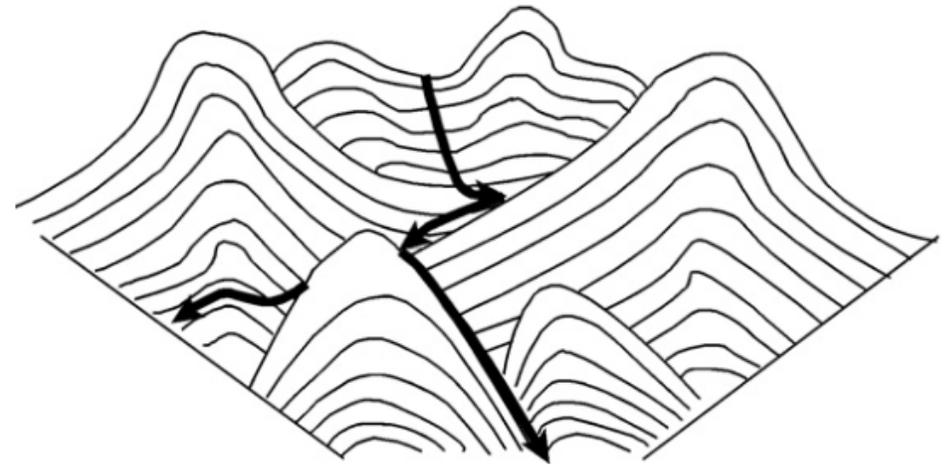
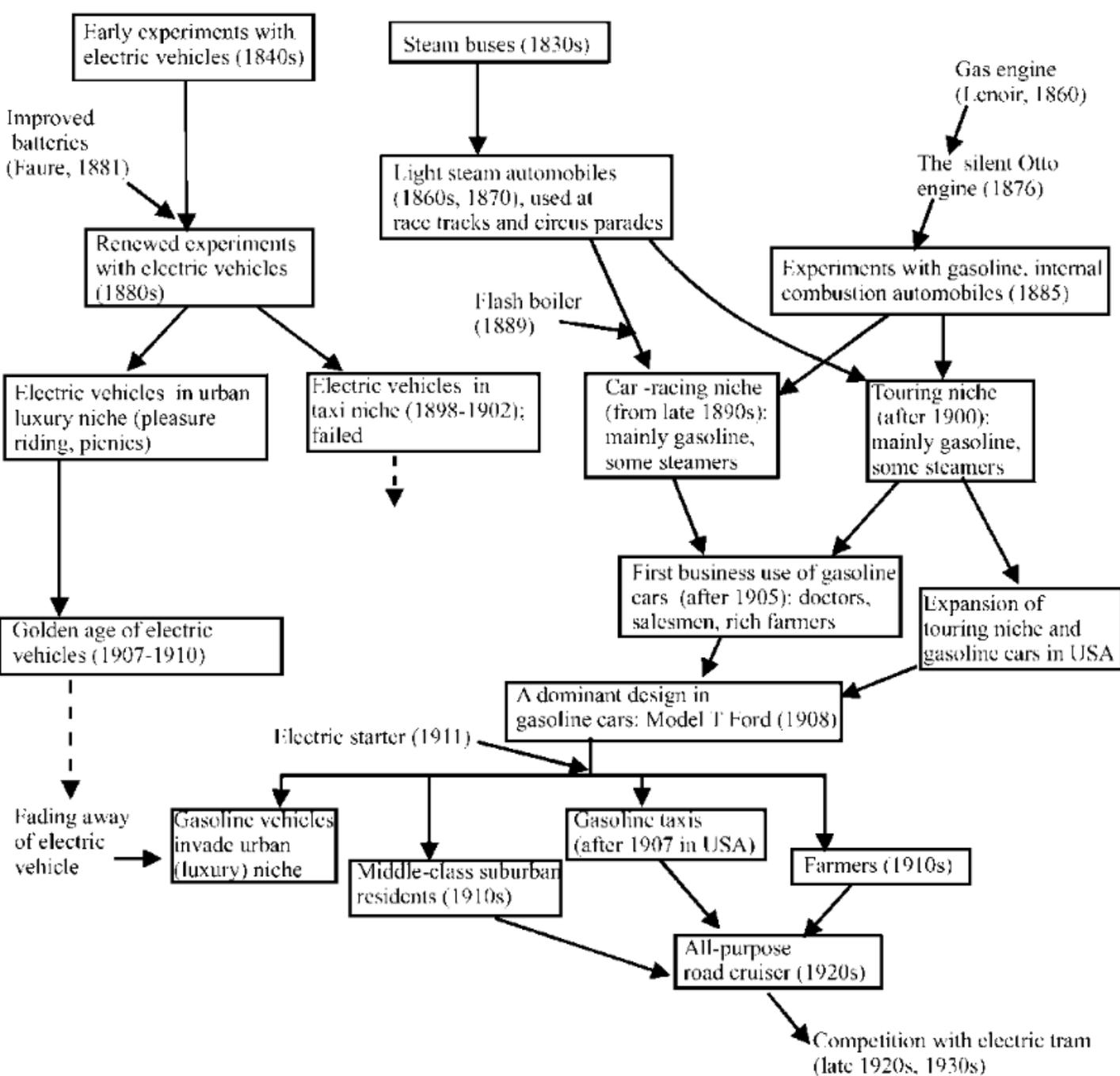


Fig. 3. Topography of development trajectories (Sahal, 1985, p. 79).

Right:  
 Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. *Research Policy* 36, 399–417.  
<https://doi.org/10.1016/j.respol.2007.01.003>

Left:  
 Geels, F.W., 2005. The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). *Technology Analysis & Strategic Management* 17, 445–476. <https://doi.org/10.1080/09537320500357319>

Figure 10. Trajectory of niche accumulation for the emergence and diffusion of automobiles

# Contemporary pathways and Systemic Innovation

## **Evers Adalbert; Nowotny Helga, Über den Umgang mit Unsicherheit: Die Entdeckung der Gestaltbarkeit von Gesellschaft (1987)**

- Uncertainty not just as technical problem but an overall social and cultural challenge (social phenomenon)
- The quest for security shapes social structures, policies, and knowledge systems
- Security Paradox: Efforts to create security often generate new uncertainties
- Societies continuously seek to transform uncertainty into manageable forms (security, risk, regulation)
- From collective guarantees (community-based) to institutionalized systems (social insurance, welfare state)
- Modernity reframes uncertainty as risk, enabling technical and economic management
- Managing uncertainty becomes a principle of social design, requiring adaptive governance
- Transition from viewing threats as uncontrollable dangers to framing them as calculable risks. Risk management techniques (insurance, regulation) become central to modern governance

# Contemporary pathways and Systemic Innovation

**Jasanoff, Sheila (2004). The idiom of co-production. In S. Jasanoff (Ed.), States of Knowledge: The Co-Production of Science and Social Order (pp. 1–12). Routledge. DOI: 10.4324/9780203413845**

- Science and society are not separate spheres; they co-produce each other. Scientific knowledge and social order evolve together through institutions, norms, and practices.
- Scientific facts and social norms are intertwined; governance influences research priorities, and science legitimizes policy
- Technology and knowledge are embedded in cultural, political, and institutional contexts—not universal or value-free
- Calls for foresight and public participation in shaping emerging technologies (e.g., biotech, AI, climate engineering)
- Scientific models shape climate governance, while political priorities influence model assumptions

# Contemporary pathways and Systemic Innovation

**Mazzucato, Mariana (2021). Mission Economy: A Moonshot Guide to Changing Capitalism. Penguin Books. ISBN: 9780241419731**

- Governments should not only fix market failures but actively shape markets by setting bold, strategic missions that address societal challenges (e.g., climate change, health, digitalization)
- Inspired by the Apollo program (“moonshot thinking”), missions mobilize resources toward transformative objectives
- Missions require coordination between public, private, and civil society actors
- Policies should ensure equitable access and long-term societal benefit

# Contemporary pathways and Systemic Innovation

**Murthy, Sharmila L. (2024). Disrupting Utility Law for Water Justice. Stanford Law Review**

- **Distributional Justice:**  
Who gains and who bears costs in technology transitions? Avoid reinforcing inequalities
- **Procedural Justice:**  
Inclusive decision-making processes; affected communities should have a voice
- **Recognition Justice:**  
Acknowledge diverse cultural and social contexts in technology design and governance
- **Intersectionality:**  
Consider overlapping vulnerabilities (e.g., poverty, race, gender) in transition planning.

# Chapter 3 – Systems Modelling and Systems Engineering

1. Cybernetics & Systems Theory
2. Technologies embedded in value chains
3. Process Engineering > Systems Engineering
4. Model Based Systems Engineering (MBSE)
5. Graph Theory & Network Complexity
6. System Integration Impact Assessment (SIIA)

# Cybernetics and Systems Thinking

## **Biological systems**

- Human nervous systems
- Ecosystems

## **Feedback & control**

## **Homeostasis & adaptation**

## **Open vs closed systems**

## **Emergent properties**

## **Technical systems**

- Aircraft autopilot
- Industrial process control

## **Social systems**

- Economy
- Healthcare system

## **Complex networks**

- Internet
- Transportation Network

# Foundations of Systems Thinking: Cybernetics & General System Theory

## Norbert Wiener (1894–1964)

Mathematician

*Cybernetics: Or Control and Communication in the Animal and the Machine* (1948)

- Introduced feedback loops for system regulation
- Unified biological and mechanical systems under principles of communication and control
- Laid foundations for automation, robotics, and AI
- Emphasized information flow as central to system stability

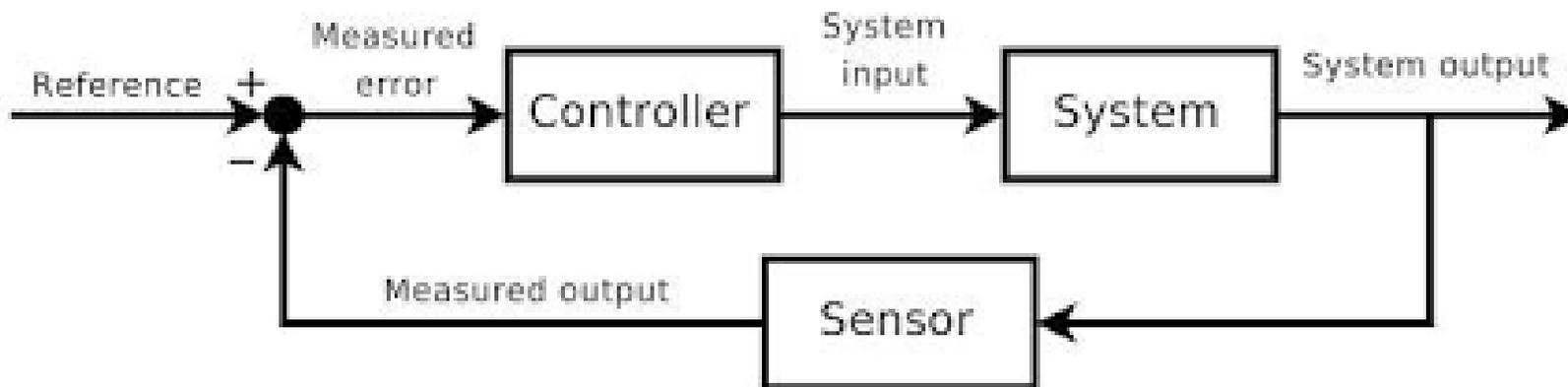
## Ludwig von Bertalanffy (1901–1972)

Biologist

*General System Theory* (1968)

Introduced feedback loops for system regulation

- Proposed open systems concept: exchange of matter, energy, and information
- Advocated for holistic modeling beyond reductionism
- Influenced ecology, organizational theory, and engineering
- Highlighted emergent properties in complex systems



# Foundations of Systems Thinking: Cybernetics & General System Theory

Cybernetics → too far ahead of its time

Interdisciplinary theory on the fundamental functioning of biological, social, technical systems

→ check the Macy conferences, their method of bringing together perspectives, and their participants

Collection of abstract principles which lacked sensory and controller capabilities for testing and application

Was informed by other interdisciplinary movements such as from psychology (Gestalt theory), engineering (Control theory), early software engineering (Information theory), from neurophysiology, biology, anthropology, sociology

Informed many interdisciplinary movements > into systems engineering for large-scale projects (aerospace, ..), artificial intelligence, complexity science and network theory, architecture and design (Bauhaus), art & media

Niche today (AI, robotics, cognitive science) even though capability restrictions of 75 years ago don't apply anymore (big data for social systems, proper understanding of the biological cell and interactions)

# Cybernetics application

## Project Cybersyn

Stafford Beer (1926 – 2023) invited by President Salvador Allende

3D render of the Operations Room (Opsroom) in Chile 1971 – 1973 (!)



<https://upload.wikimedia.org/wikipedia/commons/6/6f/CyberSyn-render-107.png>

## New Tools for Management:

*The whole nation - Central Government - State economy – Industry - One branch – one sector – one line – the firm – department – workshop - crew - worker*

Telex machine for „online“ reporting and economic mapping



<https://boot-boyz.biz/products/cybersyn>

# The rise of Systems Engineering

**Context:** Post-WWII era – large-scale, complex projects:

- Dual use nuclear industry
- Aerospace and space race
- Industry needs for reliability, interoperability, cost control
- Formalization of international standards and methods for requirements, design, testing

**IIASA**      **ITER**  
**Bell Laboratories**    **CERN**  
**RAND Cooperation**  
**NASA**      **MIT**    **ETH Zürich**  
**Santa Fe Institute**  
**Max Planck Institute**  
**Stockholm Resilience Center**

From cybernetics → holistic approach – treat entire system as an integrated whole

Lifecycle thinking: From concept → design → operation → decommissioning (TRLs!)

Interdisciplinary coordination: mechanical, electrical, software, human factors ...

# Excursion – International Institute for Applied Systems Analysis IIASA

> Founded during the Cold War to build bridges between based on international interdisciplinary science and cooperation

Member states (accession dates)



International Institute for Applied Systems Analysis

Austria (1973)	Ukraine (1994)	Iran (2016)
Finland (1976)	Norway (1996)	South Korea (2008)
Germany (1972)	China (2002)	Slovakia (2020)
Japan (1972)	Egypt (2003)	Vietnam (2013)
Russia (1972)		Israel (2017)
Sweden (1976)		Sub-Saharan Africa (2022)
USA (1972)		United Kingdom (2015)
		India (2007)

# International, intergovernmental, academic



## Programs of IIASA

Advancing Systems Analysis	Biodiversity and Natural Resources	Economic Frontiers	Energy, Climate, and Environment	Population and Just Societies	Strategic Initiatives
Research groups ▾	Research groups ▾	Research fields ▾	Research groups ▾	Research groups ▾	Current initiatives ▾
Cooperation and Transformative Governance (CAT)	<b>Agriculture, Forestry, and Ecosystem Services (AFE)</b>	Economics of Equal Life Chances (EELC)	Integrated Assessment and Climate Change (IACC)	Equity and Justice (EQU)	
Systemic Risk and Resilience (SYRR)	Biodiversity, Ecology, and Conservation (BEC)	Economics of disruptive change (EDC)	Integrated Climate Impacts (ICI)	Migration and Sustainable Development (MIG)	
Exploratory Modeling of Human-natural Systems (EM)	Integrated Biosphere Futures (IBF)		Pollution Management (PM)	Multidimensional Demographic Modeling (MDM)	
Novel Data Ecosystems for Sustainability (NODES)	Water Security (WAT)		Sustainable Service Systems (S3)	Social Cohesion, Health, and Wellbeing (SHAW)	
			Transformative Institutional and Social Solutions (TISS)		

# Excursion – multilateralism on technology development

**OSCE** Organization for Security and Co-operation in Europe

**IEA** International Energy Agency

**UN** United Nations

- Division for Sustainable Development Goals (DSDG) -> UN Energy (2004)
- IPCC Intergovernmental Panel on Climate Change
- IPBES Intergovernmental Panel on Biodiversity and Ecosystem Services
- IAEA (International Atomic Energy Agency) – CTBTO Comprehensive Nuclear-Test-Ban Treaty
- UNFCCC (Framework Convention on Climate Change) Green Climate Fund, Global Environment Facility
- IMF (International Monetary Fund)
- FAO (Food & Agriculture Organization)
- SE4ALL (Sustainable Energy for All)

**IRENA** International Renewable Energy Agency since 2009

**CEM** Clean Energy Ministerial

**MI** Mission Innovation

**ISO** International Organization for Standardization, **IEC** International Electrotechnical Commission

**REN21** Inter-governmental organisations, NGOs, Industry Associations, Governments, Academia

**CGIAR** Research on food security

Others: *International Energy Forum (IEF), GBEP, BioFuture Platform, EurObserv'ER, EREC, World Energy Council*

# Formalization of Systems Engineering

## **Sankey diagrams (Riall Sankey 1853 – 1925):**

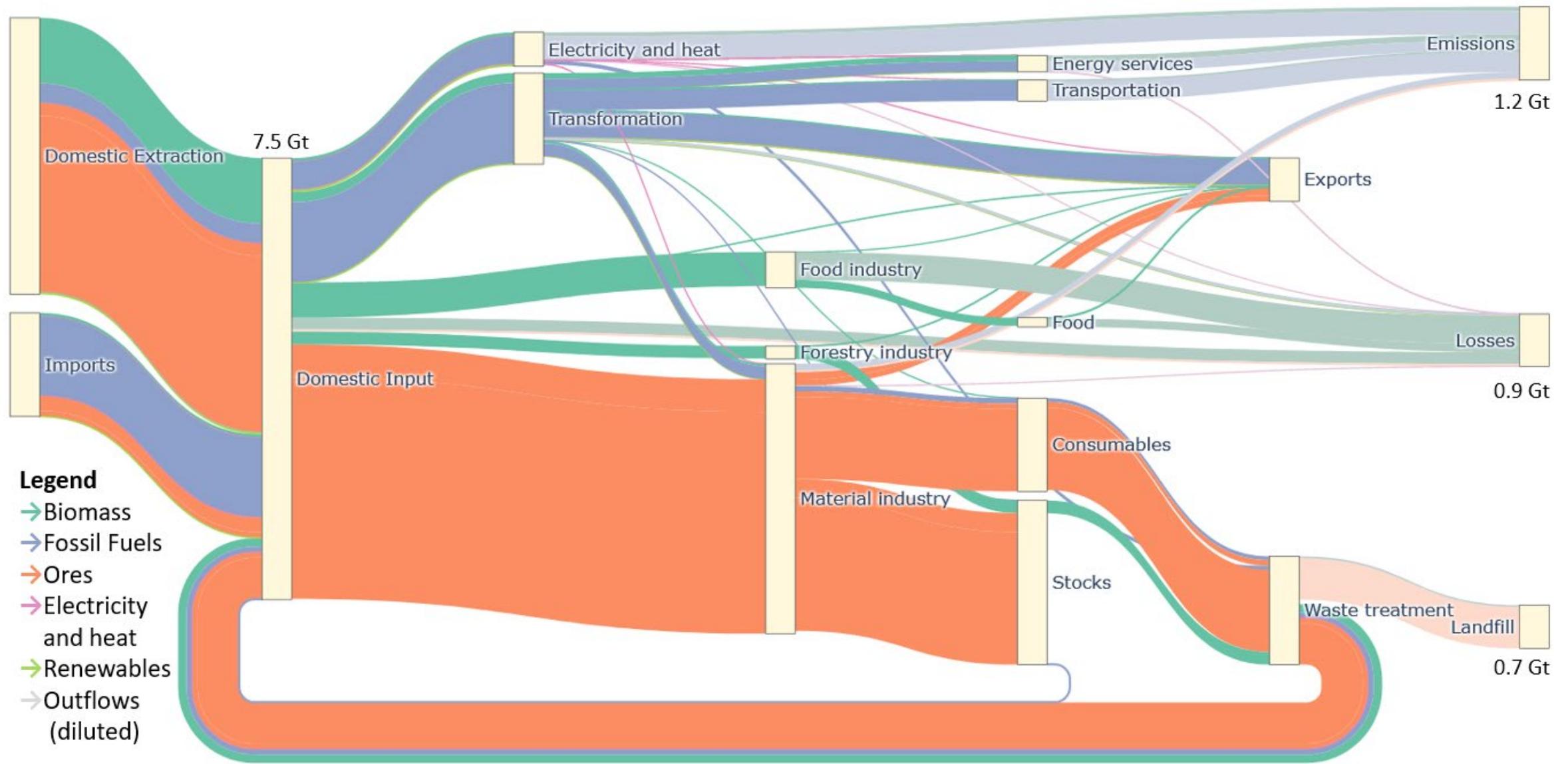
- used already to optimize steam engines – since 1896 (<https://doi.org/10.1680/imotp.1896.19564>)
- use arrow thickness to represent the magnitude of energy or material flows within a system
- help visualize resource efficiency and identify losses in industrial processes and economy wide

## **Forrester diagrams (Jay Forrester 1918 – 2016):**

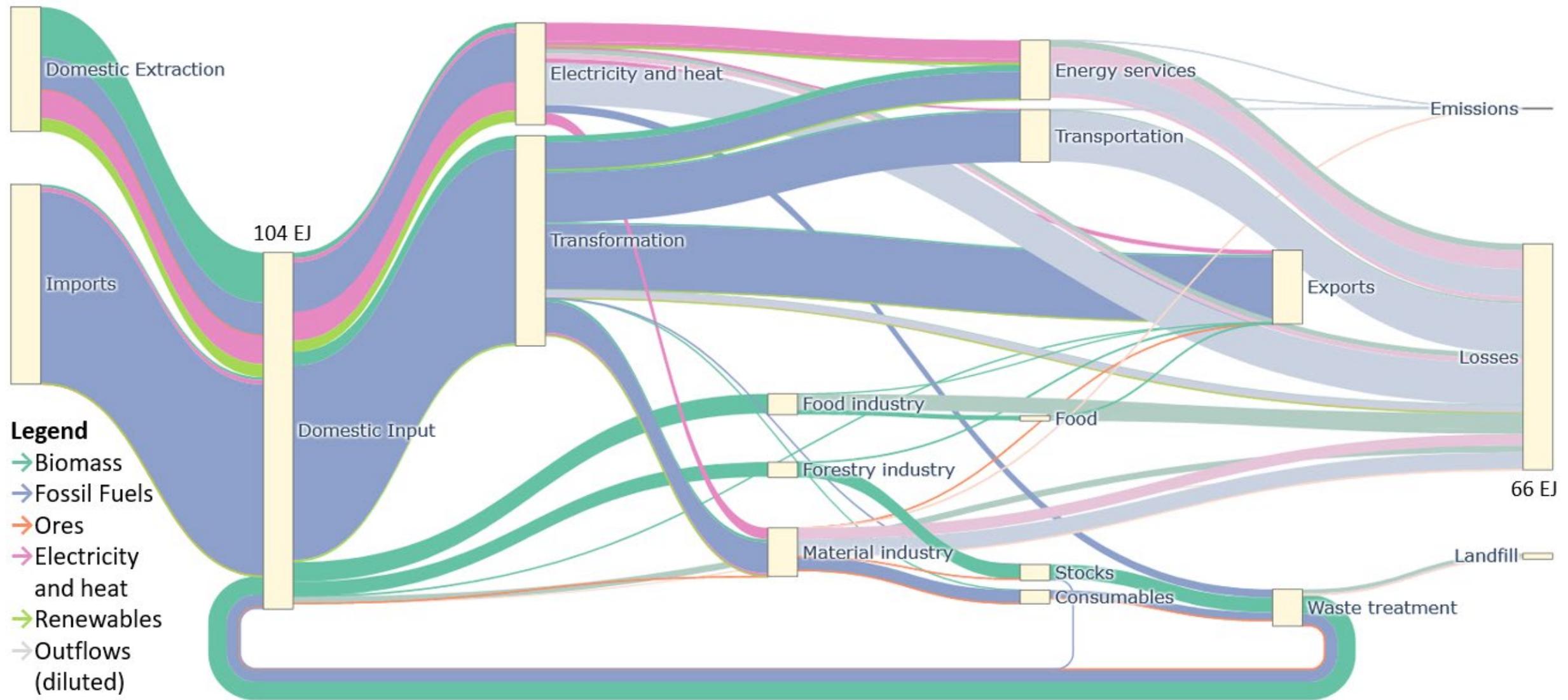
- Visually represent stocks, flows, and feedback loops to model complex systems' dynamics over time
- Reinforcing and balancing feedback loops illustrate how system variables influence growth and stability respectively.
- Forrester diagrams help anticipate unintended outcomes and design resilient interventions across sectors like energy and transportation.

## **Formalization of causal loop diagrams and system dynamic modelling:**

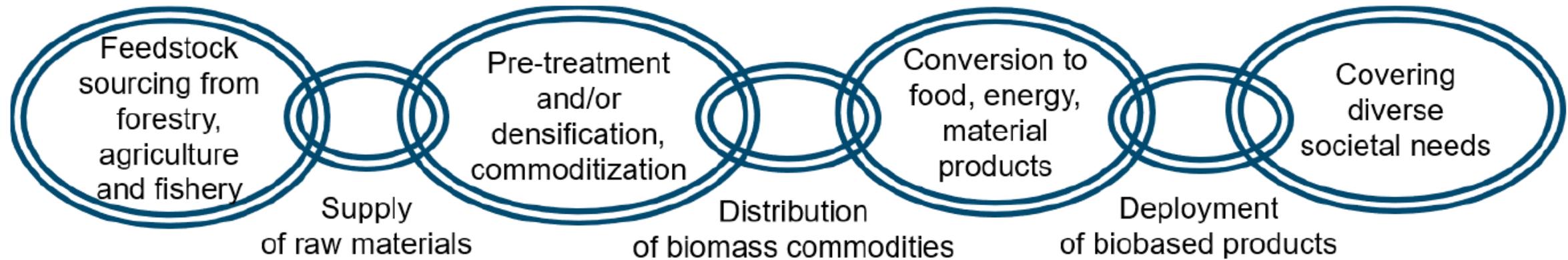
- depict feedback mechanisms that influence system behavior using arrows and polarity signs
- used in policy, industrial planning, and sustainability to identify leverage points and risks



Schipfer, Fabian, Pralhad Burli, Uwe Fritsche, et al. "The Circular Bioeconomy: A Driver for System Integration." *Energy, Sustainability and Society* 14, no. 1 (2024): 34. <https://doi.org/10.1186/s13705-024-00461-4>.



# Value chain perspective



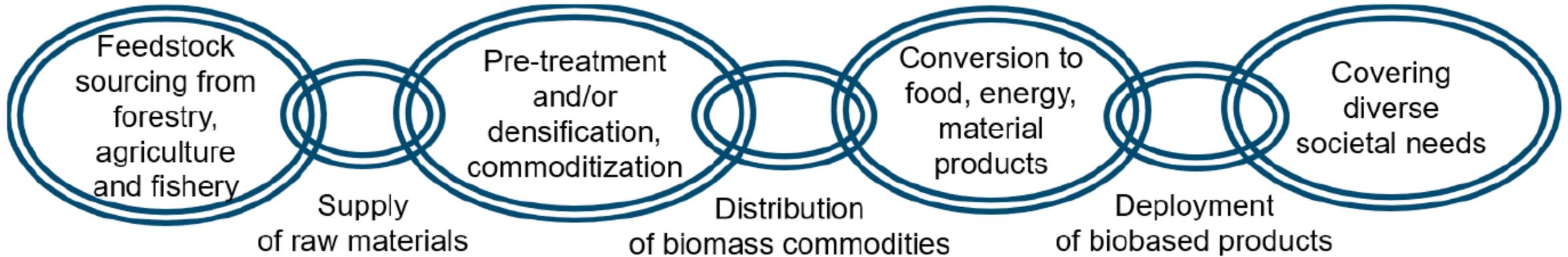
- Biophysical processes
- Ecosystem services
- Participation, jobs, ownership

- Waste-management
- Technology, Infrastructure
- Economics, econometrics (markets)

- Trends & dynamics
- Macro-economics
- Policy, legal & financing, decision-making under deep uncertainty

**Schipfer, F., Kranzl, L., 2019.** Techno-economic evaluation of biomass-to-end-use chains based on densified bioenergy carriers (dBECs). *Applied Energy* 239, 715–724. <https://doi.org/10.1016/j.apenergy.2019.01.219>

# Value chain perspective



Agriculture residues (corn stover, winery res. Beer brewery ...)

Field agents

Ecosystem services

Energy crops

Logistics

Post-harvesting

Pelletisation

Anaerobic digestion

Multiple stakeholders

Bio-hubs

Biorefinery

Waste streams

Gasification

Branching supply chains -byproducts/co-products

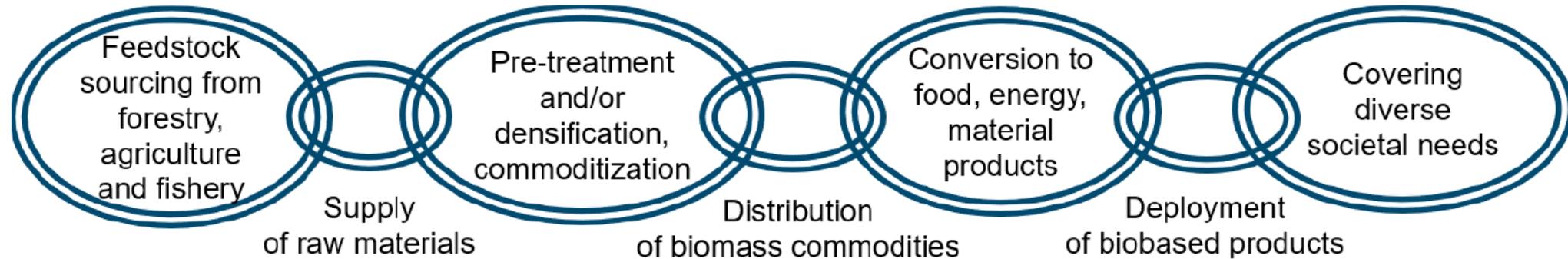
Bioenergy policies

Competitive markets

Bioeconomy strategies

Multiple modes

# Value chain perspective



<b>Sourcing benefits</b>	<b>Distribution benefits</b>	<b>Deployment benefits</b>
<ul style="list-style-type: none"> <li>• Stakeholder diversification</li> <li>• Multi-level value creation and decision making</li> <li>• Green jobs, jobs, jobs</li> <li>• Biosphere link &gt; Taking care of a changing environment</li> </ul>	<ul style="list-style-type: none"> <li>• Networks of networks -&gt; ability to shift resources between different networks</li> <li>• Flexibility and reconfigurability to react to uncertainties in sourcing and demand</li> </ul>	<ul style="list-style-type: none"> <li>• from cost-efficient services to sufficient and equitable services</li> <li>• resilience and reliability, safety and security</li> <li>• for conscious waste management and much more</li> </ul>

# Formalization of Systems Engineering

## **Control Theory & Optimization (PID Control)**

- origin in automatic control systems; formalized mid-20th century
- PID (Proportional–Integral–Derivative) controllers regulate system output by adjusting input based on error
- ensures stability, accuracy, and performance in dynamic systems
- applied in process control, robotics, energy systems, and aerospace

## **Quality Control Movement (Statistical Process Control):**

- developed by Deming and Juran (1950s)
- uses statistical methods and control charts to monitor process variability and detect deviations
- foundation for Six Sigma and Total Quality Management
- improves reliability and reduces defects in manufacturing and engineering

## **Pinch Analysis & Process Integration:**

- introduced by Bodo Linnhoff (1980s) for energy efficiency
- identifies pinch point for optimal heat recovery in industrial processes
- reduces energy consumption and environmental impact
- applied in chemical plants, refineries, and integrated energy systems

# Formalization of Systems Engineering

## **Block diagrams, V-model:**

- used to represent system architecture and functional decomposition
- V-model formalizes the systems engineering lifecycle: design on the left, verification and validation on the right
- ensures traceability from requirements to implementation and testing
- applied in aerospace, automotive, and large-scale infrastructure projects

## **Life Cycle Analysis (LCA):**

- assesses environmental impacts across all stages of a product or system's life
- includes raw material extraction, manufacturing, use, and end-of-life disposal
- supports sustainability decisions and circular economy strategies standardized by ISO 14040 series

## **SysML, MBSE frameworks:**

- SysML (Systems Modeling Language) provides a formal way to model system requirements, structure, and behavior
- MBSE (Model-Based Systems Engineering) replaces document-centric approaches with integrated models
- enables simulation, digital twins, and interdisciplinary collaboration
- widely used in aerospace, defense, and complex industrial systems

# Graph Theory & Network Complexity

from geometry to topology to networks and networks of networks

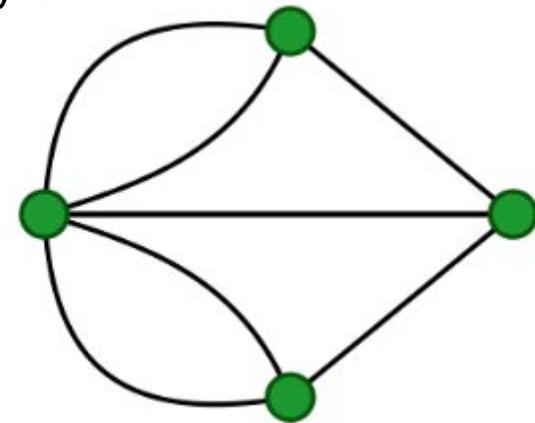
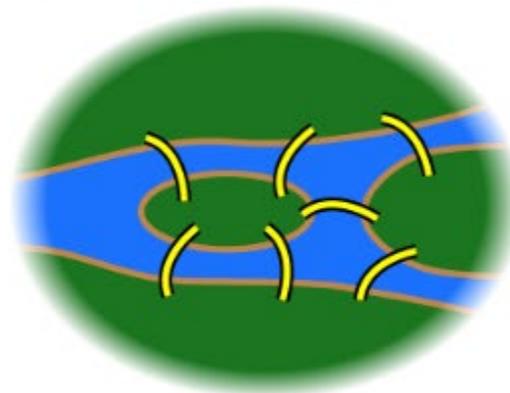
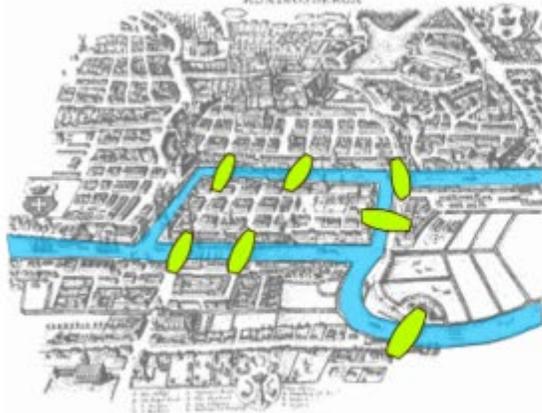
formalized for engineering and computer science in the 20th century

used to represent systems as nodes and edges, enabling analysis of connectivity, flows, and resilience

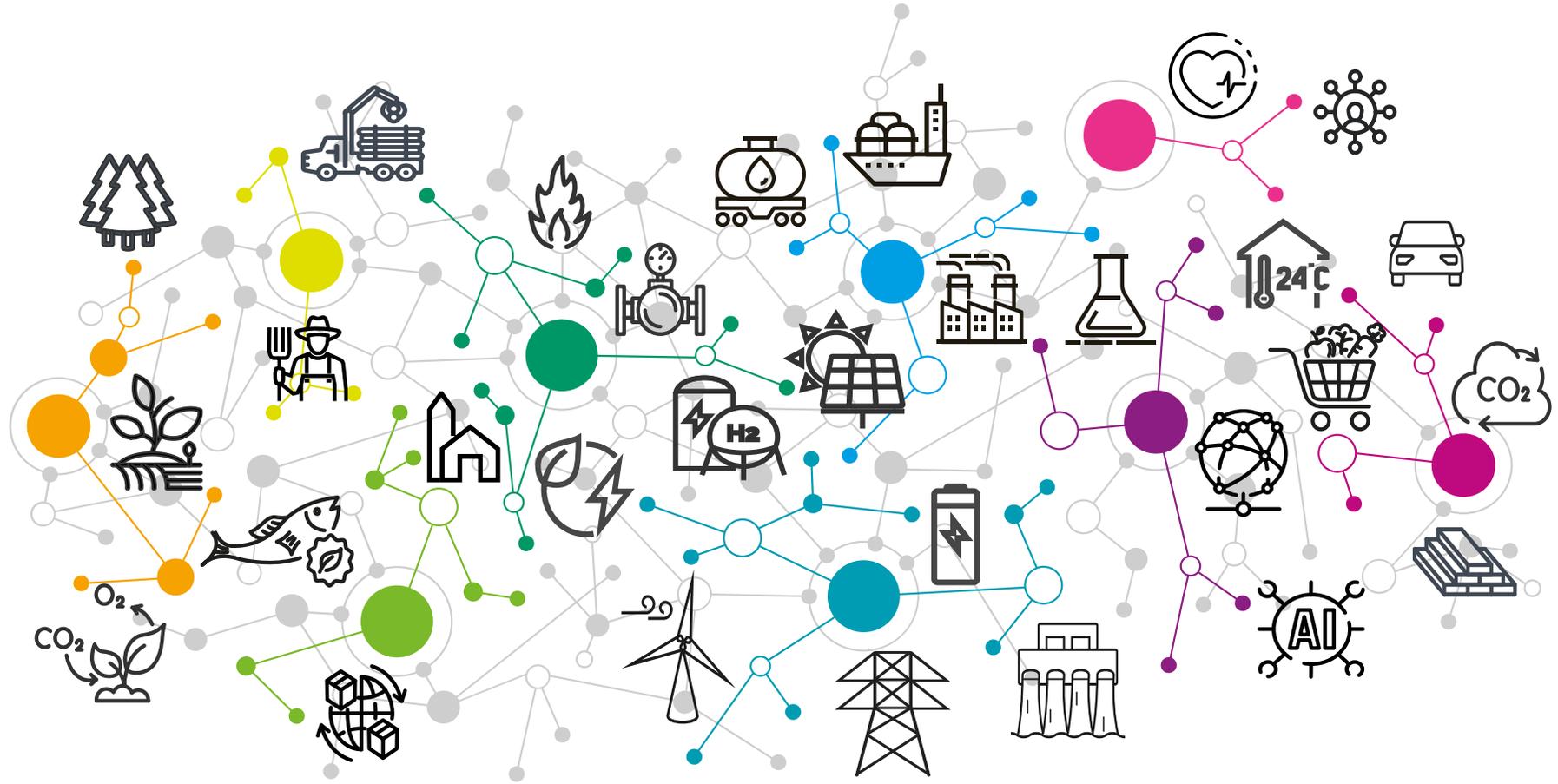
applied in energy grids, transportation networks, supply chains, and socio-technical systems

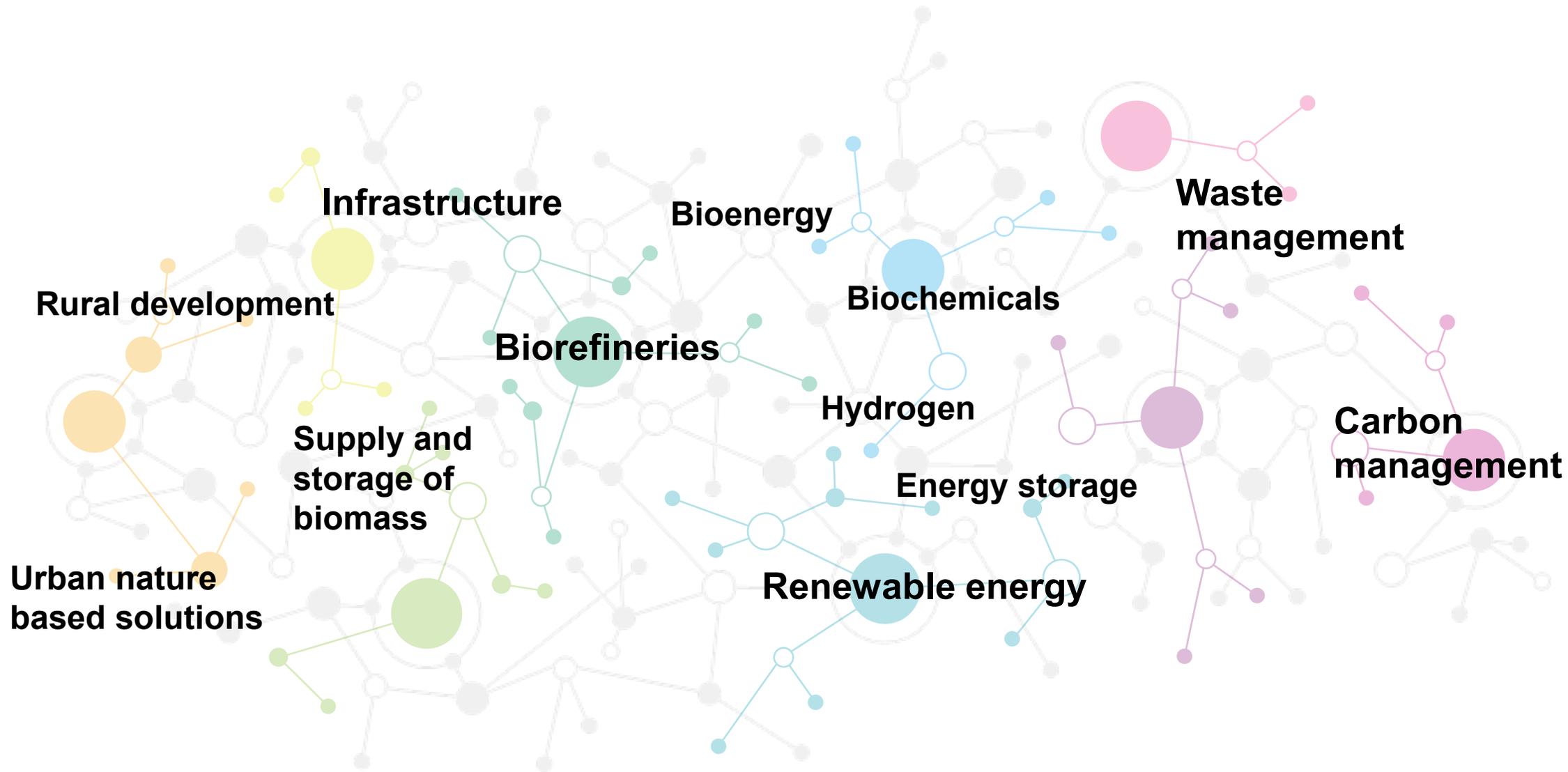
Königsberg bridges problem: Leonhard Euler (1707 – 1783)

Topological proof that there is no path that crosses each bridge only once



[https://de.wikipedia.org/wiki/K%C3%B6nigsberger\\_Br%C3%BCckenproblem](https://de.wikipedia.org/wiki/K%C3%B6nigsberger_Br%C3%BCckenproblem)





# Graph Theory & Network Complexity

## **Jennifer Chayes (1956– )**

pioneered research in network theory and algorithmic foundations

working on probabilistic models for large-scale networks and complexity

led interdisciplinary teams at Microsoft Research and UC Berkeley

advocating for diversity and ethics in computing and network science

Graph partitioning - Used in cloud computing and distributed systems - efficient algorithms for big data networks

## **Lada Adamic (1971– )**

Developed first models for social network analysis and information diffusion

studying community structures and influence patterns in online networks

contributing to understanding resilience and vulnerability in social systems

## **Réka Albert (1972– ) & Albert-László Barabási (1976 - )**

co-developed scale-free network theory

researching network robustness and cascading failures

applying network science to biological and infrastructure systems

Cascading failures between power grids, transportation networks, and communication systems

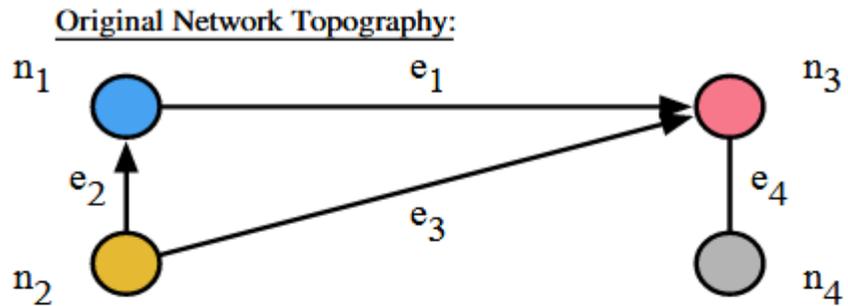
# Hetero Functional Graph Theory

**Amro Farid**

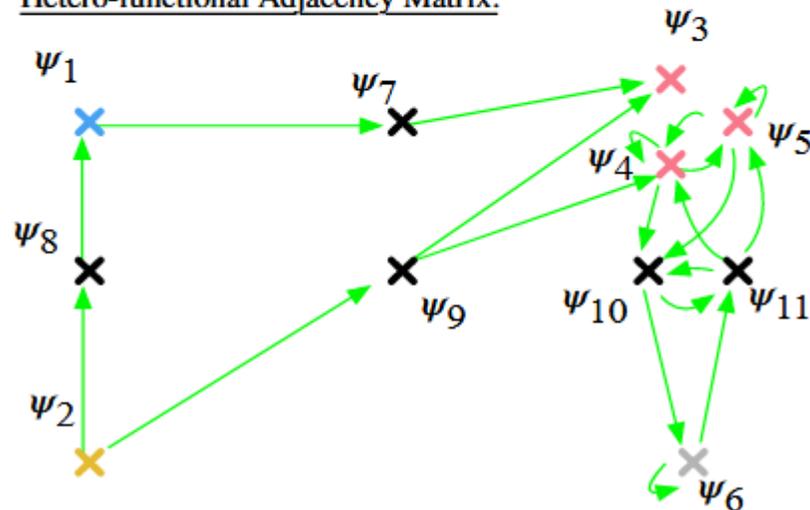
Traditional graphs focus on one resource

HFGT considers different types of resources

Formalizes the utilization of Model Based Systems Engineering



Hetero-functional Adjacency Matrix:



**Legend:**

Nodes:

- $n_1$ : Water Treatment Facility
- $n_2$ : Solar PV
- $n_3$ : House
- $n_4$ : Work Location

Edges:

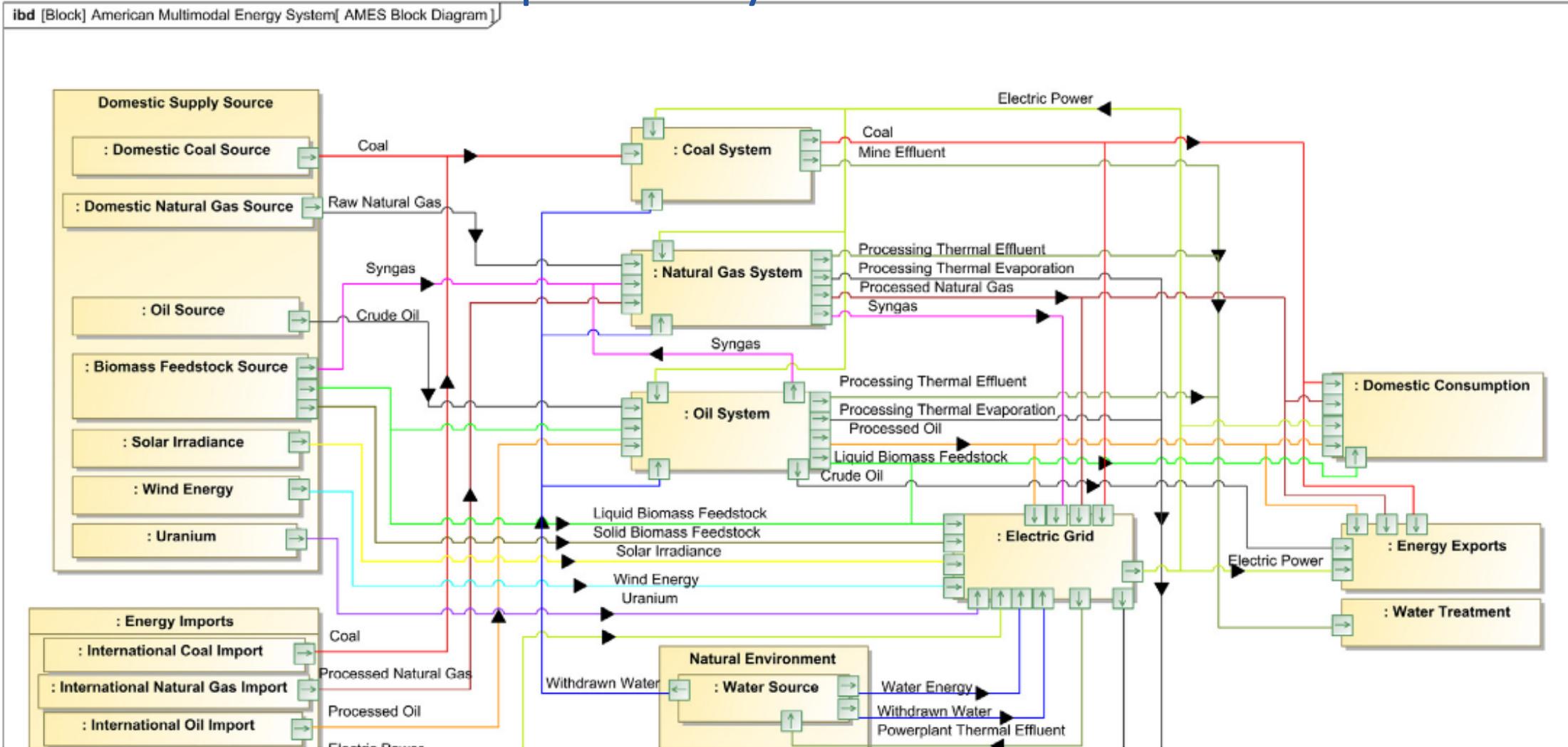
- $e_1$ : Water Pipeline
- $e_2$ : Power Line 1
- $e_3$ : Power Line 2
- $e_4$ : Road

Degrees of Freedom:

- $\psi_1$ : water treatment facility treats water
- $\psi_2$ : solar PV generates electricity
- $\psi_3$ : house consumes water
- $\psi_4$ : house charges EV
- $\psi_5$ : house stores parked EV
- $\psi_6$ : work location stores parked EV
- $\psi_7$ : water pipeline transports water from water treatment facility to house
- $\psi_8$ : power line 1 transports power from solar PV to water treatment facility
- $\psi_9$ : power line 2 transports power from solar PV to house
- $\psi_{10}$ : road discharges EV from house to work location
- $\psi_{11}$ : road discharges EV from work location to house

Fig. 1. A comparison of a traditional graph and a hetero-functional graph  
 Thompson, Dakota J., Wester C.H. Schoonenberg, and Amro M. Farid.  
 "A Hetero-Functional Graph Analysis of Electric Power System Structural Resilience."  
 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), IEEE, February 2020, 1–5.

# Hetero Functional Graph Theory



Thompson, Dakota J., and Amro M. Farid. "A Reference Architecture for the American Multi-Modal Energy System Enterprise." *Journal of Industrial Information Integration* 36 (December 2023): 100521. <https://doi.org/10.1016/j.jii.2023.100521>.

# System Integration Impact Assessment

→ Integration (complexification) as a central activity driving human development

- Solid, liquid, gaseous fuels > heat > work > power > data
- Process integration, process intensification, heat network synthesis
- Combined heat and power, district heating, international grids, power and internet
- Sector coupling and electrification of heating, mobility, industry
- Multisector and multi-SDG coupling, circularity, water-food-materials-energy nexus
- Integration over spatial scales, via networks, trade, multi-level governance, internet
- Integration over time scales, storages, batteries, financial instruments such as futures, insurances

→ The whole is more than the sum of its parts ....  $1 + 1 > 2$

→ Integration impacts can be beneficial (synergies) or negative (trade-offs, security paradox, error cascades)

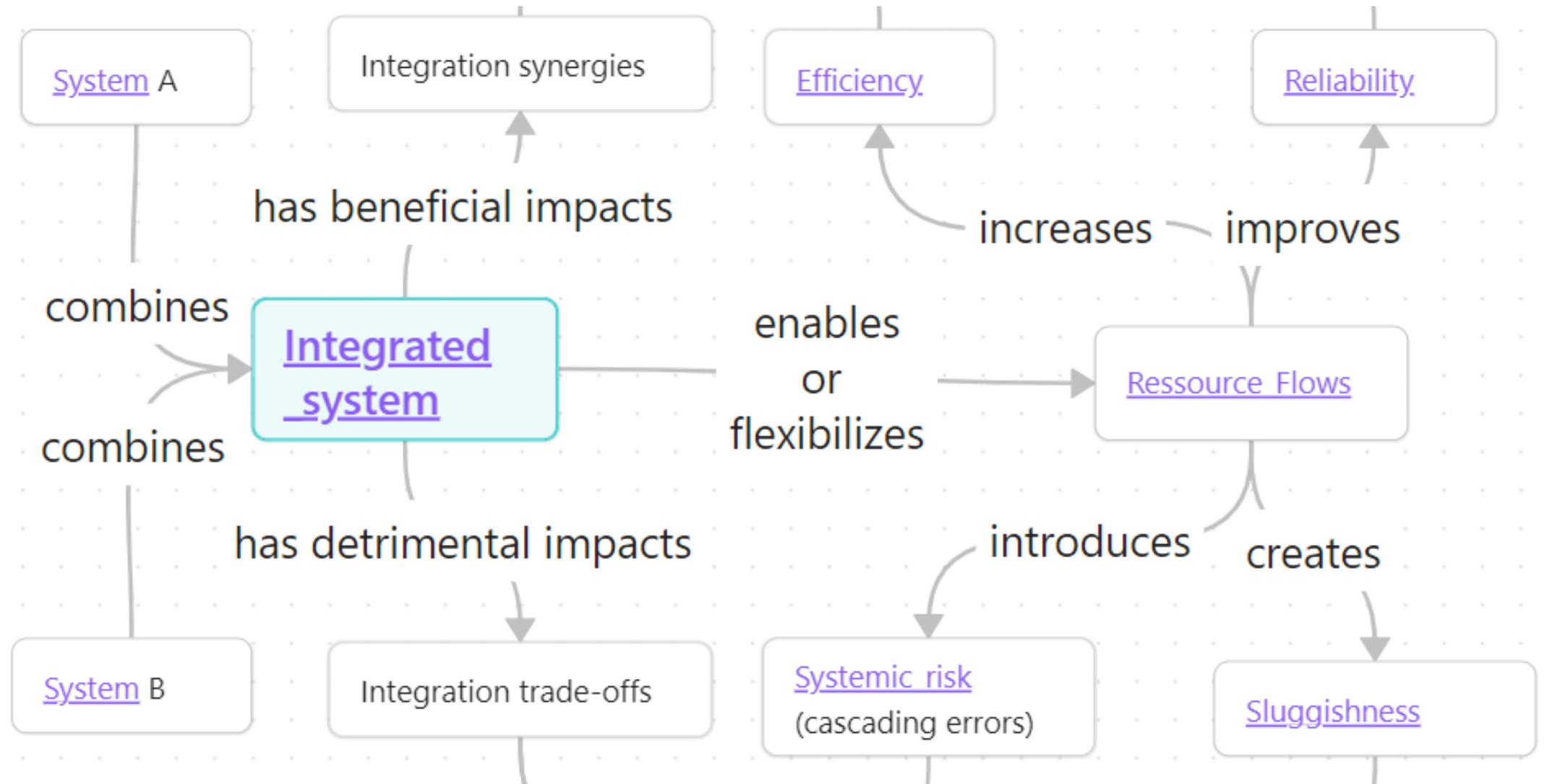
→ We need more balanced accounts of potential integration impacts

for society to amplify beneficial impacts and mitigate negative impacts of humanities development

Schipfer, F., Harasek, M., Tiwari, S., Kraxner, F., Schmidt, J., Wehrle, S., Asasian Kolor, N., Thrän, D., Esmaeili Aliabadi, D., & Breunig, H. (2025). Are we ready to plan for synergies? System Integration Impact Assessment in the Austrian Energy System Modelling Community. Accepted (06.12.2025) for publication in Energy Research & Social Science. Preprint available here:

<https://doi.org/10.5281/zenodo.17085016>

# System Integration Impact Assessment



# System Integration Impact Assessment

Earth-system  
uncertainties



Atmosphere



Biosphere



Hydro/  
Cryosphere



Geosphere

## Uncertainty types:



Trends  
(scenarios)



Variabilities  
(operations)



Extremes  
(disaster risks)



Cascades  
(climate risks)



Human-system  
uncertainties



Technosphere



Sociosphere



Cybersphere



Econosphere

# System Integration Impact Assessment

	<b>Uncertain trends</b>	<b>Uncertain variabilities</b>	<b>Uncertain extremes</b>
<b>Earth system</b> <i>Considered uncertainties in Energy SMs</i>	<i>e.g. on global warming</i>	<i>e.g. on weather seasonality and day-nighttime</i>	<i>e.g. on climate extremes</i>
<b>Human system</b> <i>Considered uncertainties in Energy SMs</i>	<i>e.g. on socio-economic trends</i>	<i>e.g. on costs and prices, on trade</i>	<i>e.g. on accidents, market crashes, wars, cyber-threats</i>

**Decreasing Modelling Readiness Levels – potential evolution?**



# Biases and Language – Challenges for Interdisciplinary Integration

- We are in the age of rising bias awareness, intercultural sensitivity, and pluralistic literacy
  - Biases and language shape perceptions, decisions, and collaboration
  - Daniel Kahneman on cognitive biases, affinity, attribution, confirmation biases  
2002 Nobel price in economic science
  - Helga Nowotny – Language of uncertainty in science
  - Ruth Schwartz Cowan on gender and technology narratives
  - Timoty Morten – Hyperobjects – no single person can have an overview
- Bringing together and combining diverse perspectives ultimately results in better decisions
- Creating safe spaces for diverse teams valuing its multi-perspective is an integration activity in itself
- How can we support multi-perspective synthesis in our impact assessments?
  - Participatory methods (e.g. foresight workshop)
  - Develop shared ontologies, glossaries, thesaurus
  - Boundary objects (e.g. models, diagrams) to bridge disciplines – multi-level consistency

# Annex – Relevant prizes to watch out for and examples

Name	Prize Type	Year	Citation
Herbert A. Simon	Nobel Prize in Economic Sciences	1978	for work on decision-making in organizations and bounded rationality.
John F. Nash Jr.	Nobel Prize in Economic Sciences	1994	for pioneering work in game theory.
Daniel Kahneman	Nobel Prize in Economic Sciences	2002	for having integrated insights from psychological research into economic science, especially concerning human judgment and decision-making under uncertainty.
Intergovernmental Panel on Climate Change (IPCC)	Nobel Peace Prize	2007	for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change.
Al Gore	Nobel Peace Prize	2007	for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change.
Barbara Liskov	ACM A.M. Turing Award	2008	for contributions to programming language and system design—data abstraction, fault tolerance, distributed computing.
Elinor Ostrom	Nobel Prize in Economic Sciences	2009	for her analysis of economic governance, especially the commons.
Bruno Latour	Holberg Prize	2013	for an ambitious analysis and reinterpretation of modernity; advancing Science & Technology Studies.
Sir Tim Berners-Lee	ACM A.M. Turing Award	2016	for inventing the World Wide Web, the first web browser, and the fundamental protocols and algorithms allowing the Web to scale.
Paul M. Romer	Nobel Prize in Economic Sciences	2018	for integrating technological innovations into long-run macroeconomic analysis.
Esther Duflo	Nobel Prize in Economic Sciences	2019	for their experimental approach to alleviating global poverty.
Emmanuelle Charpentier	Nobel Prize in Chemistry	2020	for the development of a method for genome editing (CRISPR-Cas9).
Jennifer A. Doudna	Nobel Prize in Chemistry	2020	for the development of a method for genome editing (CRISPR-Cas9).
Syukuro Manabe	Nobel Prize in Physics	2021	for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming.
Klaus Hasselmann	Nobel Prize in Physics	2021	for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming.
László Lovász	Abel Prize	2021	for foundational contributions to theoretical computer science and discrete mathematics, and their leading role in shaping them into central fields of modern mathematics.
Avi Wigderson	Abel Prize	2021	for foundational contributions to theoretical computer science and discrete mathematics, and their leading role in shaping them into central fields of modern mathematics.
Sheila Jasanoff	Holberg Prize	2022	for pioneering research in Science and Technology Studies; co-production, sociotechnical imaginaries, and civic epistemologies.



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