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Science of Intelligence Developing Perspectives on Intelligence

We examine and build
intelligent behavior
to find the principles
of intelligence

Oliver Brock | Jens Krause | Solveig Steinhardt (Eds.)

Science of Intelligence – Developing Perspectives on Intelligence

We examine and build
intelligent behavior
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science^{of} intelligence

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Science of Intelligence

Developing Perspectives on Intelligence



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Dear colleagues, friends, and inquisitive minds,

What is intelligence? Answering this question may be more important today than ever before. Artificial intelligence (AI) is transforming our world at a speed and on a scale unlike most technologies that came before it. But is today's AI intelligent in the same sense that we consider humans intelligent? We need to address this question – and many others like it, ideally before our use of AI leads to unintended and irreversible consequences. More than ever, we need a deeper understanding of what it means to be intelligent.

Over the past seven years, the Cluster of Excellence Science of Intelligence (SCIoI) has brought together researchers from twelve disciplines to pursue precisely this challenge. By studying humans, animals, robots, and artificial systems, we have searched for recurring patterns that give rise to intelligent behavior. We regard these recurring patterns as candidates for principles of intelligence.

These principles provide a conceptual framework and, more importantly, a path toward a deeper scientific understanding of intelligent behavior itself. Our collective work within SCIoI has led us to the view that different forms of intelligence, whether found in humans, animals, robots, or even plants and fungi, may share some of the same underlying mechanisms.

This perspective broadens the concept of intelligence, perhaps even extending it to all forms of life. Some may find such a definition too inclusive, but I am personally drawn to the idea that intelligence is a fundamental property of living systems. Indeed, the principles that generate adaptive, goal-directed behavior may be part of what distinguishes the animate from the inanimate.

The pages that follow present this perspective, the scientific evidence that has shaped it, and the many discoveries and open questions that have led us to our current understanding of intelligence.

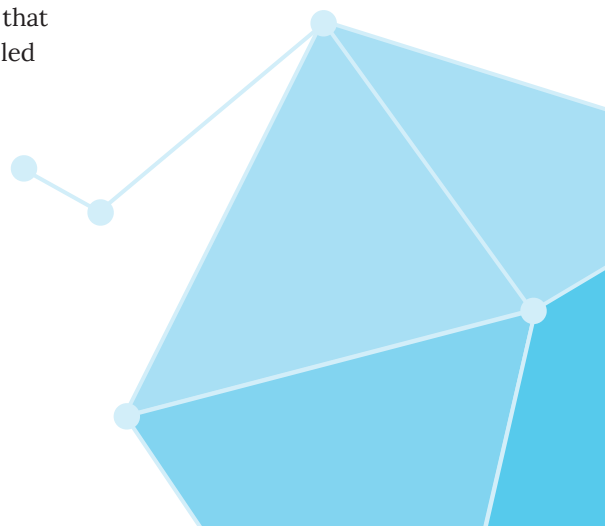
Thank you for joining us on our quest to understand intelligence!



Oliver Brock
SCIoI Spokesperson



Oliver Brock – SCIoI Spokesperson





About SClOl

5	Preface
9	About This Book
10	Cluster Milestones
12	How Our Research Works
16	The SClOl Legacy



Research Perspectives

20	The Future of Science of Intelligence
24	Still Ahead of the Curve
26	How to Merge Different Disciplines
29	A Whole Buffet of Intelligent Behaviors
32	Research Highlights:
	• From Animals to Robots
	• The Collective Brain
	• Improving Robotic Vision
	• What is Intelligence?
42	Open Science... of Intelligence
47	Teaching the Next Generation
50	The SClOl Effect

Contents



Candidate Principles of Intelligence

- 54 From Recurring Pattern to Candidate Principle
- 58 The Candidate Principles of Intelligence
- 60 Five Facts about the Principles of Intelligence
- 64 [Active Interconnections](#)
- The Robot That Didn't Need a Plan
- 68 [Multiple Computational Paradigms](#)
- A Body That Knows
- 72 [Agent-Environment Coupling](#)
- The World Does All the Work
- 76 [Adaptive Representations](#)
- Context Changes Meaning
- 80 [Multimodality](#)
- Lessons from Nature on Multimodal Intelligence
- 84 [Multi-Timescale Computation](#)
- Seeing with Purpose
- 88 [Incremental Assembly of Capabilities](#)
- Learning, Step by Step
- 92 [Adaptation of Structure](#)
- The Liquid Brain
- 96 [Separating Information into General and Instance-specific](#)
- Teaching Robots to Generalize

Insert Conceptual Foundations

- ii Unifying Research on Biological and Artificial Intelligence

Making it All Happen

- 100 What is a Cluster of Excellence?
- 101 Communication Achievements
- 102 How to Run a Cluster
- 106 SCIOI in Numbers
- 108 Saved by the Cockatoos
- 110 What Then Must We Communicate?
- 112 Diversity Beyond Boxes

People

- 116 Selected Grants and Awards
- 118 People

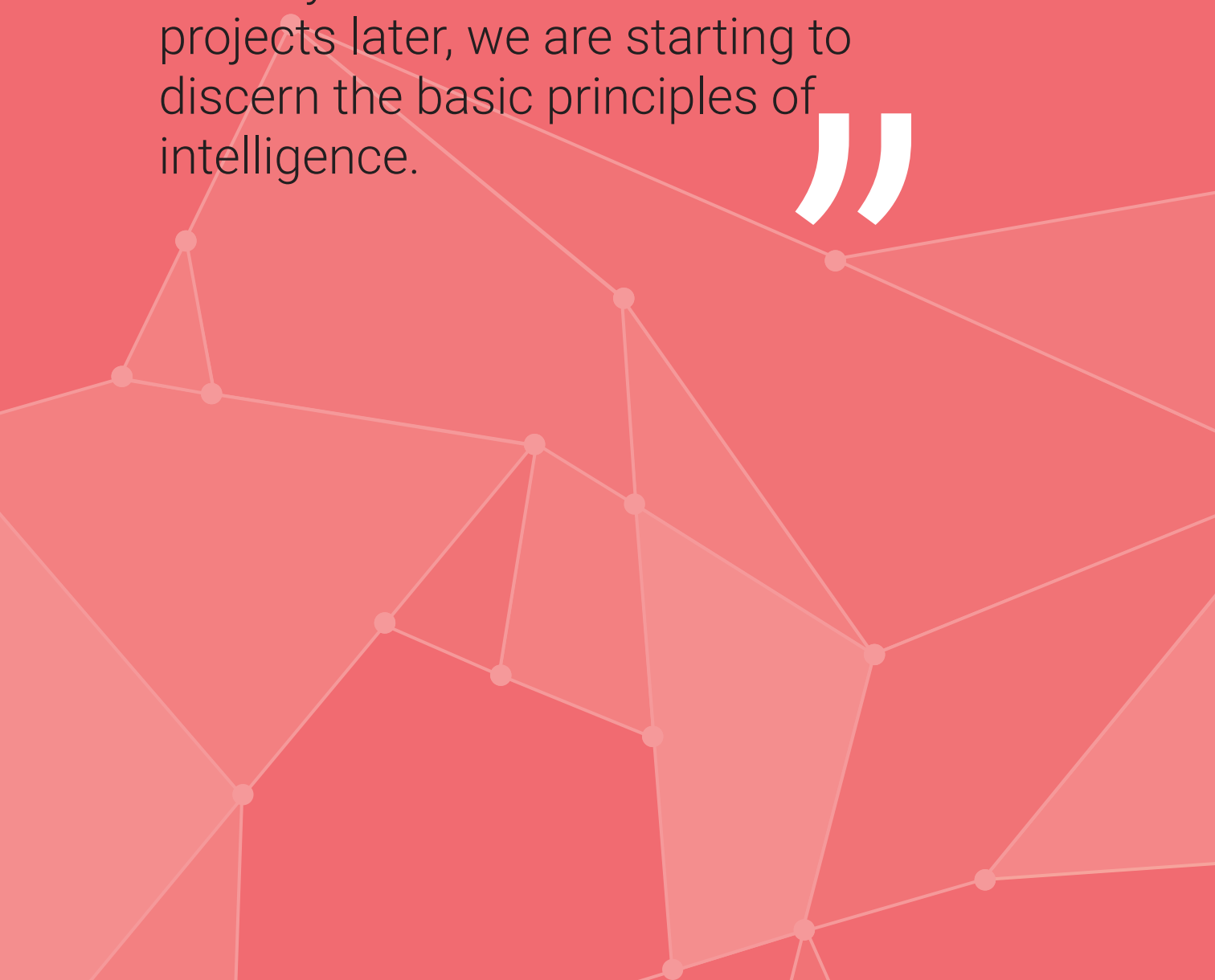
Publications

- 131 Research Highlights
- 134 All Publications
- 170 Research Data
- 173 Doctoral Theses

“

What are the principles of intelligence, shared by all forms of intelligent beings, no matter whether artificial or biological, human, or animal? When we started, finding an answer to this question was the one central objective of our Cluster. Seven years and 52 scientific projects later, we are starting to discern the basic principles of intelligence.

”



About This Book

Although we are still far from a unified definition of intelligence, the past seven years of Science of Intelligence (SCIoI) have marked significant progress towards understanding it. By bringing together diverse research groups and perspectives, SCIoI has fostered unprecedented interdisciplinary collaboration, integration, and the exchange of ideas across fields. Together, these achievements have allowed researchers to identify common patterns across different forms of intelligence, and these have laid the foundation for the next and most ambitious step: extracting general principles of intelligence.

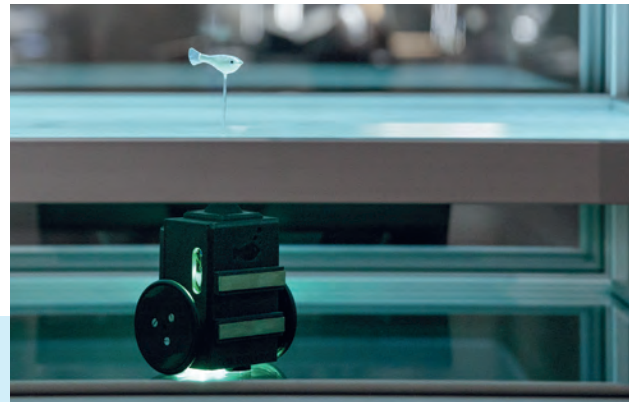
This book guides readers through this journey, starting with what we call the “analytic-synthetic loop” (p. 12), a cycle in which we seek to understand natural intelligence in order to replicate it in machines, meanwhile also using those efforts to learn more about natural intelligence itself. From there, it explores the behaviors that characterize intelligence (p. 14), highlights key research findings,

and ultimately presents what may be the principles that guide intelligent behavior (from p. 52). Each principle is explained, illustrated, and further brought to life through contributions from our researchers, who describe how it manifests in their own work.

Readers interested in a deeper exploration of the research will find an academic summary of these findings in the Conceptual Foundations insert, while the following chapter (p. 99) offers insights into the coordination and management of a Cluster of Excellence. We hope you enjoy reading this book.

BY SOLVEIG STEINHARDT

SCIoI’s Robofish, a highly realistic biomimetic robotic fish designed to study intelligence, collective behavior and animal-robot interaction.



Useful terminology

Agent: an entity (biological or artificial, individual or collective) that perceives, acts, and adapts under resource limitations within an environment characterized by uncertainty.

Analytic versus synthetic research: Analytic research studies biological intelligence. Synthetic research synthesizes technological artifacts such as robots to investigate intelligence by building it.

Descriptive model: model that captures the measurable properties of a (behavioral) phenomenon.

Mechanistic model: a descriptive model that also captures the process that leads to the phenomenon.

Regularity: a consistently recurring, predictable, and describable relationship between characteristics of a system.

Robustness: a robot’s ability to operate consistently and preserve its performance in real-world conditions, even when facing malfunctions, inaccuracies, or unforeseen inputs.

Tinbergen’s Four Questions: four questions used to explain how a behavior physically happens and develops, and why it evolved to aid survival.

SCIoI: short for “Science of Intelligence,” pronounced sy-oh-eye

Cluster Milestones

2019

Hello, World!

SCIOI receives funding from the German Research Foundation (DFG) to conduct seven years of intelligence research.

February 2021

Scientists and Citizens Imagine the Future Together

Thanks to BUA (Berlin University Alliance) funding, SCIOI and EXC Matters of Activity set up a joint “Experimental Lab for Science Communication” called “CollActive Materials,” bringing citizens together to imagine and design futures with intelligent materials.

June 2021

SCIOI Featured in Humboldt Forum Exhibition

The Humboldt Forum museum hosts the exhibition *Nach der Natur*, showing the fragility of nature through objects, videos, and simulations from all seven of Berlin’s Clusters.

2021–2025

Winter Schools, Summer Schools

SCIOI co-organizes many educational programs: the annual Winter School “Ethics of Neuroscience and AI” (BCCN, SCIOI, and the School of Mind and Brain), the SCIOI and ISAB Summer School (SCIOI and ISAB), and the Berlin Summer School on Artificial Intelligence and Society (SCIOI, BIFOLD, and the Weizenbaum Institute).

November 2021

Brand-New Labs

The SCIOI labs are ready for scientists to move in: These include the Čapek Lab, the Asimov Lab, the Visual Capture Lab, the Media Lab, and the EEG Lab.

March 2021

GSEP Fellowships Program

Through the Global Scientific Exchange Program (GSEP), SCIOI grants six fully funded, three-month fellowships to Master’s-level students who will visit the Cluster from across Africa in the summer.

May 2023

Podcast Launched

A team of SCIOI researchers launches *Punching Cards*, the podcast about *all things intelligent*, featuring stories, anecdotes, and interviews about intelligence research.

September 2023

The SCIOI Fair

Politicians, scientists, and the public visit the SCIOI Fair, an interactive, all-day event about Science of Intelligence.

2027 and beyond

Looking to the Future

As this first chapter of SCIoI comes to an end, we are as eager as ever to continue our research and to add new disciplines and elements to what is now an established research subject: the science of intelligence. Stay tuned for more news and surprises as we continue our journey towards the discovery of what guides intelligence.

October 2026

SAB 2026

SCIoI supports the 18th International Conference on the Simulation of Adaptive Behavior, part of the ISAB series "From Animals to Animats".

May 2026

430+ Publications

Research progresses at a steady pace. In May 2026, SCIoI celebrates its 430th publication.

December 2025

A New Strategy for Future Research

SCIoI PIs meet and brainstorm about the path SCIoI will take in the coming years.

June 2025

"SCIoI 2" Not Funded

SCIoI is not among the Clusters selected for funding in 2026–2032. Nevertheless, the research continues.

January 2025

A Trip to Bonn

A team of 14 PIs travels to Bonn to present the "SCIoI 2" project.

September 2024

The Intelligence Lectures

The Berlin Senate provides funding for nine teaching projects. SCIoI early-career researchers organize Master's courses addressing key topics for students (see p. 47).

July 2024

The SCIoI Report Is Published

The *SCIoI Report 2024* provides an accessible overview of SCIoI's work to date, written for both scientific audiences and the interested public.

August 2024

Proposal Submitted for a New Round of Funding

SCIoI presents its proposal for a new round of DFG funding. If funded, "SCIoI 2" will expand its horizons towards evolutionary biology, further exploring candidate principles of intelligence.

How Our Research Works

The Analytic-Synthetic Loop

The mission at Science of Intelligence is to identify the fundamental principles of natural intelligence and apply them to the development of intelligent artificial systems. In other words, we observe intelligence in the natural world and try to reproduce it as artifacts that give us better insights into natural intelligence. It's a cycle, and we call it "the loop."

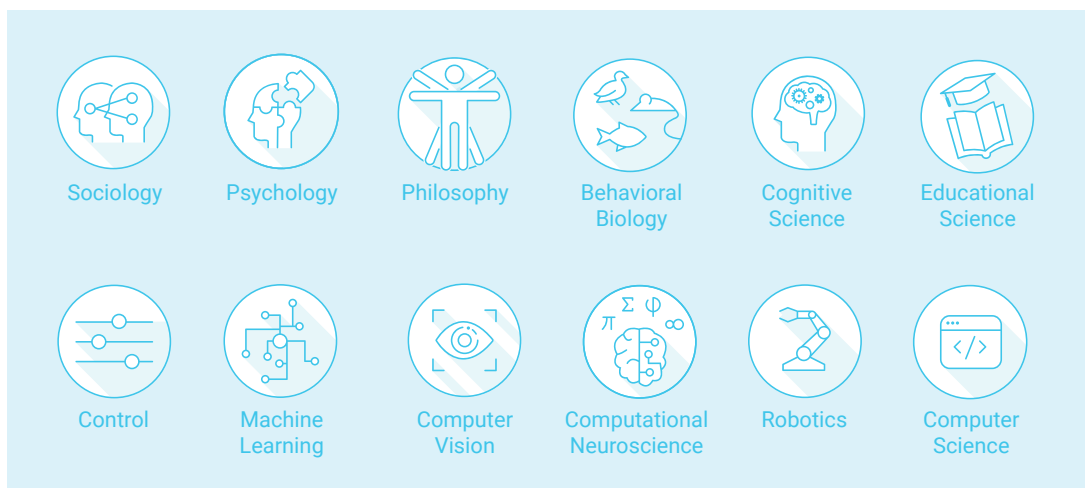
Intelligent behavior cannot be fully understood by looking at its individual functions or components in isolation. Instead, it emerges from the interaction of many processes, and it is essential to consider its elements together and how they function as an integrated whole.

To address this complexity, at SCIOI we deliberately combine different research traditions and methods. One way to do that is to take the analytical, or natural, disciplines such as biology and psychology and bring them

together with engineering-based (i.e., synthetic) approaches. On the analytical side, researchers study intelligent behavior in natural systems such as humans and animals in order to identify the principles that underlie intelligence. On the synthetic side, these principles are translated into technical applications, for example by designing and building robotic systems or other artificial agents.

Crucially, these two perspectives continuously inform and challenge one another as a

An overview of the different disciplines that study intelligence. Bringing them together allows a comprehensive analysis of intelligence.

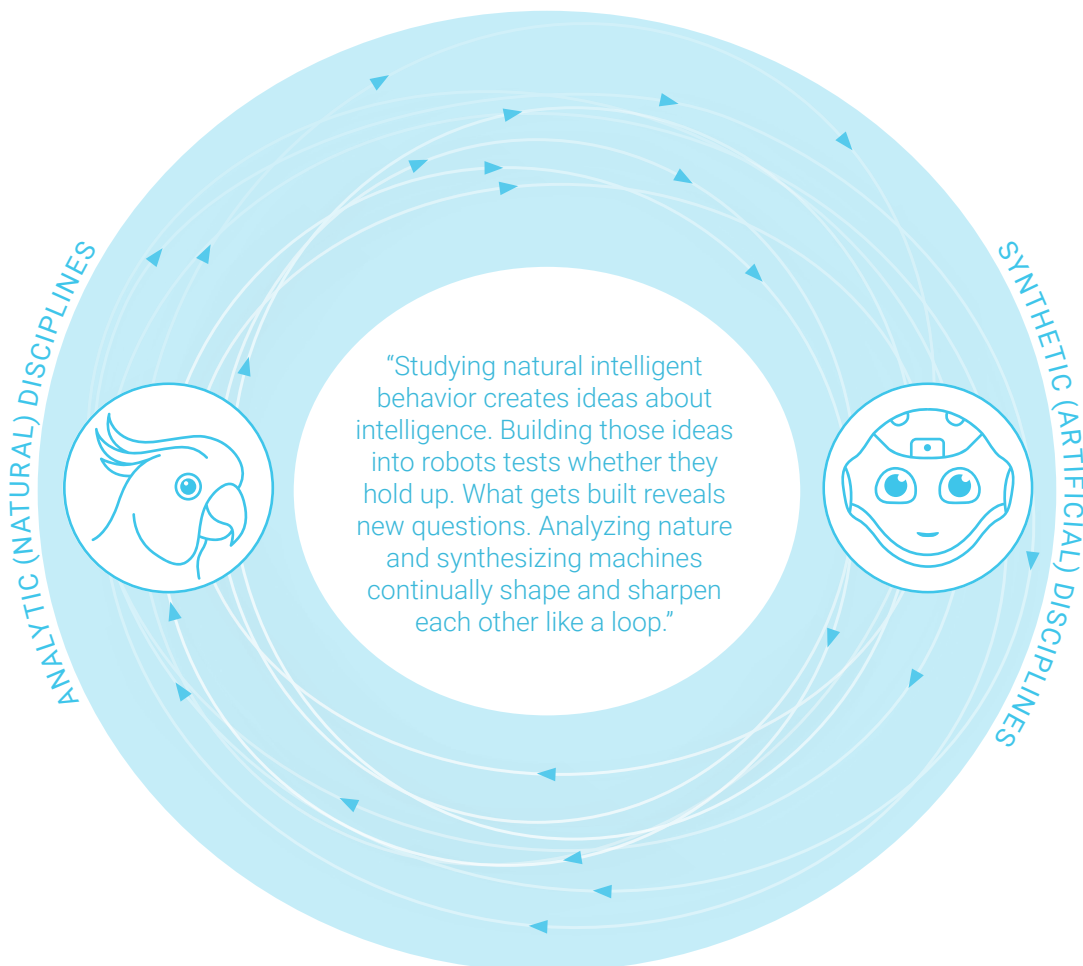


cycle. To build intelligent robots, we apply what we already know from nature, but the building process itself also provides a way to test ideas, reveal limitations, and refine our understanding of natural intelligence. This ongoing exchange creates what we call the “analytic-synthetic loop”: Constructing intelligent machines helps us better understand natural intelligence, while insights from nature guide and inspire technological innovation.

Research Units

When the Cluster was founded, the idea of an analytic-synthetic loop allowed us to organize our scientific research into four research units, with each unit based on a different research question.

The projects of [Unit 1](#) examined intelligent behaviors in nature and attempted to synthesize them, i.e., reproduce them in synthetic agents. From these results, projects of [Unit 2](#) extracted general principles of intelligence, which we further developed within technical systems in a next step in [Unit 3](#). This research strategy was accompanied by ongoing evaluation of the ethical and philosophical parameters of intelligence research in [Unit 4](#). The 52 resulting projects, spread across the four units, encompassed various topics including collective intelligence in fish, decision making, robots and animals solving escape rooms and lock-boxes, human-robot communication in the classroom, human and robotic vision, as well as ethics and philosophy.



The Example Behaviors

In addition to belonging to a specific research unit, each SClol project also falls into one of three subunits, each pertaining to a specific type of intelligence, and exemplified by a corresponding intelligent behavior. These example behaviors are chosen to capture fundamental aspects of individual intelligence, social intelligence, and collective intelligence.



Individual intelligence (Behavior 1) is attributed to a single agent (i.e., a person, an animal, or a robot) behaving in their environment (e.g., solving queries and opening locks to get out of an escape room).

Social intelligence (Behavior 2) is shown when several agents that exhibit individual intelligence interact with each other (e.g., collaboratively solving a puzzle), possibly also learning new things through social interaction.





Collective intelligence (Behavior 3) is shown by a group of agents, but in contrast to social intelligence, the resulting behavior cannot be attributed to any of the individuals but only to their collective (e.g., a swarm of fish escaping a predator, or a flock of sheep following the shepherd).

... en Route to the Principles

Seven years of intensive research at SCIOI have brought our 52 projects closer and closer to one another. Throughout this time, scientists formed increasingly strong collaborations, and disciplines converged in ways that generated new – sometimes unexpected – ideas.

From this dense exchange, we began to identify what appeared to be promising candidates for general principles of intelligence. Over time, these candidates became clearer and more numerous.

Today, we have identified as many as nine – each awaiting further exploration, rigorous testing, and demonstration by scientists around the world. In the next chapters, we will examine these principles in depth.

The SCIOI Legacy

SCIOI brought about a new way to look at interdisciplinary research. Our Principal Investigators share their thoughts.



Rasha Abdel Rahman
Psychology

“It takes a village – a village of scientists in an interactive loop of continuous exchange between disciplines – to raise our understanding of the nature of social intelligence.”

As a psychologist, I was able to get an enhanced understanding of social behavior from robotics and computer vision experts who not only analyze behavior but also synthesize it in a stimulating exchange between empirical and AI-generating disciplines across all projects. At SCIOI, we call this “the loop.” I experienced both the initial costs and the later benefits of interactive loops – between humans and robots learning to interact, and between the disciplines themselves. Just like loops, they have no end.



Alex Kacelnik
Biology

“What is intelligence, who has it, why and when does it evolve? Multiple scientific minds targeted this centuries-old enigma. Being here was both joyous and fertile.”

Crows combine multiple bits to make tools, parrots watch others solve problems and improve their skills at the first opportunity, rats sacrifice food to acquire information... Are they all intelligent? There is no single answer, but SCIOI taught us that a golden road to progress is to see what it takes to design robots that emulate them. Melting biology and robotics, psychology and AI, evolution and engineering has been SCIOI’s aim and legacy. We are much richer thanks to this.



Ralf Kurvers
Behavioral Biology

“Human decision making has evolved in a complex web of social relations and environments. Understanding human intelligence means embracing this complexity.”

Psychological research has traditionally been studying human intelligence in tightly controlled lab environments. SCIOI has pushed beyond this traditional approach by studying human intelligence in real-world environments, taking complexity as the starting point. Combining approaches from animal behavior, cognitive psychology, theoretical physics and engineering has allowed SCIOI to develop innovative methods to measure and model human decision making in the complexity of the real world.



Martin Rolfs
Psychology/Vision

“Vision is so effortless that we master it as babies, yet grasping how intelligent systems transform light into meaningful perception remains a profound scientific challenge.”

SCIoI has expanded the horizons of my field, showing how perception and vision are constrained in the broader context of intelligent behavior. Through our interdisciplinary lens, we have seen how researchers studying humans and those building robots often face similar problems. Collaboration with computer vision, control theory, and robotics gave my field new methods and conceptual tools. This enabled plausible models of perception, attention, and spatial understanding, deepening insight into biological vision and inspiring advances in synthetic systems.



Guillermo Gallego
Computer Vision/Robotics

“Robot perception provides the entry point to intelligent behavior: Sensing and extracting information about our physical world is essential to act intelligently within it.”

SCIoI’s interdisciplinary research has advanced the fields of computer vision and robot perception, with highlighted papers and repositories about bio-inspired neuromorphic (event-based) cameras. Through collaborations with Oxford University, SCIoI has shown real-world advantages of event-based systems for behavior quantification in Antarctica. With papers and surveys, published at top conferences and journals in the field, SCIoI is shaping the future of event-based robot perception, enabling more human-like robot technology.



Verena Hafner
Developmental Robotics

“Intelligence does not arise in isolation. It emerges through the interaction of body, environment, and other agents, and becomes visible in adaptive behavior.”

For me, SCIoI’s legacy lies in strengthening this embodied perspective on intelligence. The Cluster created a unique space to connect ideas from robotics with insights from cognitive science, biology, psychology and philosophy. It reinforced my view that intelligent behavior cannot be reduced to computation alone, but instead arises through sensorimotor interaction and through engagement with others. Working across disciplines made it possible to explore how individual and social intelligence are deeply intertwined.

A person with blonde hair is shown from the back, looking down. The image is partially covered by a large, stylized orange geometric shape composed of several triangles and polygons. The shape has small white dots at its vertices. The background is a blurred indoor setting.

Research Perspectives

Reflections, highlights,
and perspectives on
intelligence research

A SCIOI researcher explores how robots and humans can interact socially.



The Future of Science of Intelligence

Science of Intelligence has made significant waves over the past seven years, as this book hopefully demonstrates. But what will remain once those initial waves have subsided? What lasting impact will SCIOI have on the future of intelligence research?

BY OLIVER BROCK*



A new generation of researchers has grown up within SCIOI.

“The wisest prophets make sure of the event first.”

Horace Walpole (1717 – 1797)

The obvious answer is: the papers published, the researchers trained, the research infrastructure established, the collaborations formed, and the new ideas introduced into the field. These are substantial achievements, and in each of these respects SCIOI has excelled, as the stories and evidence presented throughout this book attest.

Yet sometimes something more happens when dedicated people come together – people united by a shared curiosity about fundamental questions while shaped by entirely different disciplines. In such an environment, new ways of thinking can emerge that extend beyond any individual project, publication, or collaboration. Our hope is that this will become SCIOI’s enduring legacy: not only the knowledge it has



produced, but also the conceptual perspectives, research questions, and interdisciplinary modes of inquiry it has brought into being. If so, SCIOI will have made a lasting contribution to our understanding of intelligence. What might that legacy look like in practice?

Joining disciplines transforms perspectives

Perhaps SCIOI's most important legacy will be the people whose scientific thinking it has transformed. Let me offer my own experience, although I suspect that many others within SCIOI would recognize something similar.

Within SCIOI, researchers from different disciplines did not merely collaborate – they shared laboratories, offices, and daily scientific life. The center made it both easy and necessary to engage deeply with colleagues whose expertise, methods, and assumptions differed fundamentally from one's own. At the time, I did not fully appreciate what an extraordinary gift this was. Looking back, I realize that it fundamentally changed how I think about science, how I view my own discipline, and ultimately the kind of research I do.

Robotics has always combined engineering and science. Through SCIOI, however, that combination evolved into something much deeper: a genuine integration. Building robots became inseparable from understanding intelligence. I now understand by building, and I build what helps me understand.

As I write this, I realize that others have expressed similar ideas before. Yet those formulations still fail to capture my own experience. In the end, you will simply have to trust me. The countless conversations within Science of Intelligence and the many lessons I

learned from colleagues in other disciplines made me a far better researcher – or at least I hope they did.

I first had to learn about the astonishing cognitive abilities and wonderfully chaotic behavior of cockatoos, with their distinctive exploration and planning strategies, before I could fundamentally rethink how robots should behave. I had to learn about Nikolaas Tinbergen's famous "four questions" (see glossary, p. 9) – which help explain how a behavior physically happens and develops, and why it evolved – to recognize how narrow the perspective of my own field had been. Only then could I ask different questions, pursue different paths, and ultimately discover different answers.

New perspectives produce new answers

In order to compare cockatoos and robots – and to discover what one can teach us about the other – we need a common conceptual foundation for intelligence. Such a foundation provides a shared language across disciplines, across biological and artificial agents, and across the many facets of intelligence itself. Only with such a foundation does it even become possible to integrate the diverse perspectives and decades of accumulated knowledge that characterize intelligence research. Developing such a perspective became

* Oliver Brock (pictured above) is a roboticist and a Principal Investigator at SCIOI. He is also the Cluster's spokesperson.

inevitable precisely because Science of Intelligence brought together researchers from many different disciplines.

The conceptual foundation that emerged from this collaboration is mechanistic (see glossary, p. 9). Rather than describing intelligent behavior itself, it seeks to explain the mechanisms that generate it. This shift is important because intelligent behavior is extraordinarily diverse. Attempting to catalog every possible manifestation of intelligence is ultimately a losing battle. Identifying the underlying mechanisms that repeatedly give rise to intelligent behavior is a far more promising scientific strategy.

Even at the mechanistic level, however, the challenge remains formidable. Mechanisms operate across multiple levels of abstraction and interact in complex ways. By comparing biological and artificial agents, studying diverse tasks, and connecting different levels of abstraction, we identified mechanistic regularities, or recurring patterns that appear repeatedly across systems – the hallmark of genuine scientific principles.

SCIoI's candidate principles of intelligence have been tested repeatedly through analytical studies of biological systems and synthetic experiments with artificial agents, as shown in the next chapter. The results (think robots that can behave efficiently without needing a previously programmed plan, p. 66, or neural processing that happens in parts of the body other than the brain, p. 70) provide compelling evidence that these principles capture general features of intelligent behavior. Researchers outside the consortium have already begun to adopt and build upon these ideas.

Whether this new framework of intelligence research will ultimately stand the test of time remains for future generations of researchers to decide. Our hope is that this book will help spread our ideas, inspire new questions, and plant seeds whose full impact might only become visible years from now.



The SCIoI robotic hand grasping a drawer handle.

A new generation for new intelligences

The future of Science of Intelligence will not be determined solely by the ideas presented in this book, but by the people who continue to develop them. A new generation of researchers has grown up within SCIoI, learning to approach intelligence not from the perspective of a single discipline but through an interdisciplinary, comparative, and mechanistic lens. Many of these researchers have already established independent research groups at universities and research institutions around the world including UC Berkeley, the Laboratoire de Physique des Solides in Orsay, and University Grenoble Alpes.

As they pursue their own scientific questions, they will inevitably take these ideas in directions we cannot yet anticipate. They will refine the conceptual framework, challenge its assumptions, extend it to new domains, and combine it with perspectives that have yet to emerge. In doing so, they will ensure that Science of Intelligence remains a living scientific endeavor rather than a completed research program. If the conceptual foundations laid by SCIoI prove valuable, it will not be because they remain unchanged, but because future generations continue to question them, improve them, and build upon them.

We hope that by presenting SCIoI's insights and ideas to you we have “made sure of the events” to a sufficient degree to be able to say that SCIoI's waves will continue to have an impact in the future! ●

“If the conceptual foundations laid by SCIOI prove valuable, it will not be because they remain unchanged, but because future generations continue to question them, improve them, and build upon them.”

Oliver Brock



Still Ahead of the Curve

As society grapples with new challenges and opportunities, several of the original SClol research objectives have become even more relevant than they were at the Cluster's outset. Looking back, we can say we have accomplished many goals, but most importantly, we started conversations that are still ongoing and laid the ground for more fundamental research.

BY MARCEL BRASS*



* Marcel Brass (pictured left) is a cognitive and social neuroscientist and a Principal Investigator at SClol.

What began as SCIoI's agenda for an interdisciplinary Cluster seven years ago has anticipated some of the central challenges that define intelligence research today. Looking back, three accomplishments stand out in particular.

We started the conversation about the principles of intelligence

Originally, SCIoI's aim to understand principles of intelligence was primarily motivated by the idea that designing artificial intelligence can largely benefit from understanding biological intelligence, which we also referred to as the "analytic-synthetic loop" (see p. 12). While this aim is still valid, recent developments in AI have created a new need for principles of intelligence. The complexity that current AI systems have reached makes it difficult to evaluate them from a pure engineering perspective, so we need a framework to evaluate and design AI that is independent of the substrate and architecture of the system. SCIoI's principles of intelligence provide such a framework. In this sense, understanding the principles of intelligence has become an even more important objective, one that SCIoI has laid the groundwork for.

We closed the gap between biological and artificial intelligence

Current generative models (i.e., machine learning models designed to create new data) are extremely successful in tasks that were completely out of reach a few years ago. However, the approach used to achieve this success also has substantial shortcomings. Unlike biological intelligence, AI is extremely data- and energy-hungry. This is where we need inspiration from biological intelligence. Sometimes small changes in the design of artificial systems can make a huge difference regarding their efficiency. But to identify and implement such relevant changes, one needs to close the gap

between biological and artificial intelligence. This is only possible in an environment where scientists from the analytic and synthetic sides directly communicate with each other. Nowadays, computer scientists carry out psychological experiments, and psychologists and biologists conduct experiments with AI. SCIoI has created an environment and a research framework that optimizes this collaboration and creates the ideal conditions for such interaction. In the optimal case, this collaboration happens in one laboratory. While disciplinary and institutional borders usually prevent such collaboration, SCIoI has used the unique opportunity of the DFG's Excellence Initiative to institutionalize this framework.

We created a common interdisciplinary language

A direct exchange between disciplines is essential to address challenges posed by recent AI developments. Researchers from different fields must find a way to communicate effectively, and this is a time-consuming, effortful process requiring extensive translation – it's easy for ideas and people to get lost in it. In an ideal world, scientists would share a common language, a kind of scientific Esperanto spoken by all, but as is known, developing and learning a language works best if you start early. One of our first goals was to develop curricula and interaction formats that support the creation of an interdisciplinary language, early on in the scientists' careers. By creating a learning environment in which computer scientists and roboticists learn fundamentals of cognitive psychology, biology, and philosophy, while psychologists, biologists, and philosophers learn the basics of AI within the same program, we are socializing the next generation of AI researchers. Hopefully in the future it will no longer be necessary to translate between disciplines. ●



How to Merge Different Disciplines

One of the strangest things about science is that researchers can spend decades studying the same phenomenon while barely understanding each other's language. A biologist, a physicist, a sociologist, and a roboticist may all be investigating intelligence, decision-making, or collective behavior – yet each approaches the problem with entirely different assumptions, methods and ways of thinking. Bringing those worlds together can be frustrating, slow and occasionally chaotic. But it's also where some of the most exciting scientific breakthroughs happen.

BY JENS KRAUSE*

* Jens Krause (pictured above, center) is a behavioral biologist and a Principal Investigator at SClol.

My personal connection to interdisciplinary thinking actually started very early in life with my older brother Stefan, who is now a professor in computer science. Ever since I was a child, he tried to interest me in mathematics. Despite my obvious lack of talent, he was endlessly patient in explaining complex ideas to me. Later on, when I studied

biology, he insisted that I learn computer languages, advanced mathematics, and graph theory. He had a huge influence on how I approached science, because he taught me that biological problems become much more interesting once you can formulate them in a way that other disciplines can engage with.



Jens Krause talks
at the Scientific
Networking Days 2025.

To me, interdisciplinarity means much more than just placing people from different fields in the same room. It means translating insights from your own discipline into a language that others can work with. Another very important prerequisite is curiosity – you have to be curious to find out how other scientists “see the world.”

At SCIoI, I experienced something fascinating: Crossing the gap between analytic and synthetic (or natural and artificial) disciplines allowed us to see our own disciplines from a whole new perspective. That process did not happen overnight and we had to spend a lot of time together, talking again and again, and learning how to communicate meaningfully across disciplinary boundaries.

One of the most memorable examples for me came when Marcel Brass (featured on p. 24) joined the Cluster and presented his work in cognitive psychology. During his talk, I suddenly realized that his approach could help investigate collective rule-breaking, a topic I had been interested in for many years. Together with Marcel, Anne Nassauer, a microsociologist, and Pawel Romanczuk, a theoretical biologist, we developed a collaboration that eventually resulted in a publication in *TiCS (Trends in Cognitive Sciences)*. That project deepened my understanding of collective behavior in ways that would never have been possible within biology alone.

What makes SCIoI unique is that it uses knowledge about intelligence to actually build synthetic systems such as robots or computational models. For scientists from analytical

disciplines like me, this part of SCIoI was essential because it forced us to explain our insights in the form of concrete algorithms instead of getting caught up in endless debates over definitions and

jargon. Finding an algorithm and building stuff that works in the real world is a refreshing

approach: it moves discussions away from endless debates over terminology and toward constructive problem-solving.

Of course, it's not always easy. In the beginning, interdisciplinarity can slow you down, and not many people are ready, or willing, to make this investment. And, there can be communication barriers: I remember early SCIoI meetings where discussions sometimes turned into a show of one's expertise rather than genuine exchange. During one talk I gave about anticipation in fish, two researchers interrupted right after I mentioned the title, and spent the rest of the session debating with each other, while I never got to present my work. It took a few months for us to get over the problem that we don't meet at SCIoI to lecture each other excessively or to show how clever we are. Experiences like that taught us that interdisciplinarity only works when people listen to each other.

Over time, SCIoI developed structures and formats that made collaboration productive and enjoyable, a common “language” that helps the understanding and advancement of complex ideas. The analytic-synthetic loop (p.12) gave us a framework that focused not on delivering a predefined product, but on creating a process for interdisciplinary discovery. That is highly unusual in academia and one of the most valuable aspects of the Cluster. ●

“Interdisciplinarity only works when people listen to each other.”



“The principles of intelligence are not a fixed menu. They are more like options in a buffet, with the intelligent ‘plates’ featuring different combinations of principles in different proportions.”

Dimitri Coelho Mollo



A Whole Buffet of Intelligent Behaviors

Intelligence shapes how we understand humans, animals, and machines. Defining it is far from simple, but philosophy can help us do that. Is it a single trait, or a mix of abilities that appear in different forms? Establishing a science of intelligence also means moving beyond rigid definitions, embracing flexibility, diversity, and even a little blurriness to better capture how intelligence shows up in the real world.

BY DIMITRI COELHO MOLLO*

The notion of intelligence is hard to characterize, let alone define. Part of the reason is that it is used in both everyday and scientific contexts and belongs to “folk psychology,” i.e., the collection of common sense ideas we use to understand ourselves and others, which we then try to refine and make more precise through science and philosophy. What makes things even more difficult is that, even within science, “intelligence” is used in different ways within and across research fields. Building a science of intelligence is a conceptual project that should be guided by two main questions: What theoretical and explanatory work do we need “intelligence” for? What specific world phenomena do we need the notion of intelligence to capture, that we wouldn’t be able to capture with the required precision without it?



* Dimitri Coelho Mollo is a collaborating PI at SCIOI and associate professor of Philosophy of Artificial Intelligence at the University of Umeå, Sweden.

In answering these questions, we should remain open to the possibility that the answer to both might be “none.” In that case, “intelligence” could be kept as an everyday concept, but should be rejected as a scientific one.

The work carried out by SCIOI over these years shows that the concept of intelligence is scientifically useful; that it can be characterized in theoretically and empirically fruitful ways; and that a science of intelligence can indeed be built. In my own work, I have argued in favor of the scientific value of the notion of intelligence. I identify a sort of behavioral “symptomatology” of intelligence that encompasses non-human animals and potential future artificial systems, and which distinguishes intelligence from related notions, such as cognition and rationality.

“Intelligence is somewhat of a fuzzy concept.”

More specifically, I suggest that intelligent systems display behaviors that are:

- general, i.e., suited to a variety of different circumstances;
- flexible, i.e., that adjust in light of changed, novel, or uncertain circumstances;
- goal-directed, i.e., aligned in light of goals that the system forms;
- adaptive, i.e., that improve or adjust based on previous interactions with the world.

In my research, I examine in more detail what each of these criteria means, but more to the point, the candidate principles of intelligence proposed by SCIOI (as I see them) help shed light on the general mechanisms that underlie and enable intelligent behavior: that is to say, behavior that displays the features I mentioned above.

Importantly, these features of behavior and their candidate underlying mechanistic principles can be realized by many different kinds of systems – humans, dolphins, corvids, and perhaps even collectives and artificial systems. This makes sure that the resulting science of intelligence does not fall into disciplinary provincialism, meeting instead the requirement to capture the many different ways in which the phenomenon of intelligence manifests itself in the world.

As often happens with concepts outside the fundamental fields such as physics or chemistry, the notion of intelligence is somewhat fuzzy (think about the notions of “cognition,” “life,” “society,” “democracy,” to mention a few). While there are clear instances of intelligent behavior, and clear instances of non-intelligent behavior, there is a broad gray area, in which systems display some features of intelligent behavior, and possibly some principles of intelligence, but only partially or to a relatively low degree.

The theoretical and empirical tools of the science of intelligence need to accommodate this fuzziness. The principles of intelligence that SCIOI identifies are indeed not to be understood as an all-in-one package. They are not a fixed menu, but more like options in a buffet, with the many possible intelligent

“plates” featuring different combinations of principles, and with each ingredient filling the plate in different proportions.

While the paradigmatic cases of intelligence – humans, bonobos, crows, etc. – have full plates, realizing all the candidate principles albeit to different degrees, we should expect many other cases to realize only some of them, having, so to speak, only some of the buffet options on their plates, and in smaller amounts. To the extent that the tools of the science of intelligence can be used to make sense of these other cases, and to the extent that this leads

to explanatory gains, it is theoretically and empirically fruitful to have the notion of intelligence encompass them as well.

Our conceptual decisions about the boundaries of intelligence, and thus of its science, should be guided by the questions mentioned above. These questions should also guide the refinement of the candidate principles. And, most importantly, they should guide the search for further principles of intelligence, the shape they happen to take in the biological systems around us, and the shape they might take in the artificial systems we build. ●

* Marten Kaas is a post-doctoral researcher at SCIOI working in the field of ethics.

Ethics first, in each project

How do we ensure that scientists conduct their research ethically? At SCIOI, we rely on both the expertise of our in-house ethicists and a structured ethics approval process to support our researchers in their cutting-edge basic research. This process, a distinctive feature of our Cluster, requires that new projects meet certain ethical standards before they begin, and provides ongoing monitoring throughout.

The process starts with an initial ethics impact assessment prepared by the project team in consultation with our in-house ethicists. If the proposal is received favorably, a second, more detailed impact assessment follows, incorporating revisions and additional project details. Once the proposal and assessment are ready, they are evaluated by our Ethics Responsibility Committee (ERC), a central component of the approval process.

The ERC can respond in several ways. It may approve the project for final evaluation, approve it conditional on minor or major revisions addressing ethical concerns, or reject it if it does not meet the required ethical standards. Importantly, rejection does not necessarily end the process. Rather, the proposal may be revised and resubmitted, often with closer guidance from our in-house ethicists to address ethical considerations earlier and more thoroughly.

Independent ethical assessment is essential, especially when research involves human and/or animal subjects or potentially socially disruptive technologies such as AI-enabled systems.

By drawing on important philosophical insights and responsible research practices, SCIOI has established a framework that helps ensure that our work meets high ethical standards.

BY MARTEN KAAS*



Above: Christa Thöne-Reineke, chair of the SCIOI Ethics Committee.

Research Highlights

At SClol, we examine and build intelligent behavior in order to understand it, and aim to identify its guiding principles so we can build intelligent and efficient robots. Here is an overview of the scientific breakthroughs that have shaped the research output of SClol since its founding in 2019.





SCIol PI Rasha Abdel Rahman gives a demonstration of her work at the EEG Lab.

Research Highlights

From Animals to Robots

Intelligence cannot exist as an algorithm alone. This is why we give it a body, often with humanoid features, that we call a “robot.” But robots are much more than just arms that can grab handles, or eyes that see farther than any human would. The robots we build need to make good decisions, adapt to a changing environment, and communicate with humans. Here are our most important discoveries.

Humans and robots are getting to know each other

What happens when a student becomes bored halfway through a lesson, or when a social robot gives too many unpredictable hints and reduces motivation? One of the study areas of SCIoI combines educational psychology, computer science, and social robotics to explore how emotions, behavior, and learning interact in real time at both the situational and personal level. Using multimodal methods – including log data, self-reports, and physiological measures such as electrodermal activity – our researchers showed that boredom and confusion can persist throughout a learning session and hinder progress, while high affective activation may drain cognitive resources and reduce knowledge gains. In contrast, enjoyment was linked to stronger engagement and better outcomes, and to the idea that adaptive social robots can promote self-regulated learning when support is personalized to learners’ needs, although poorly calibrated adaptivity may lower enjoyment. **These insights help guide the design of learner-centered educational technologies that respond not only to performance, but also to motivation.**

Chevalère, J., Yun, H. S., Henke, A., Pinkwart, N., Hafner, V. V. & Lazarides, R. (2023). *Learning and Instruction*.
 Lazarides, R., Frenkel, J. et al. (2025). *Journal of Educational Psychology*.
 Ackermann, H., Lange, A. L., Hafner, V. V. & Lazarides, R. (2025). *Scientific Reports*.*

Listen to your robotic hand. Literally

A great way to understand how soft robots interact with their environment is to “listen” to them. This method, devised by Vincent Wall and his colleagues, embeds a tiny speaker and microphone inside a soft pneumatic actuator and analyzes how sound changes as it travels through the flexible structure. Because the shape and pressure of a soft robot constantly change during motion,



these changes subtly alter sound waves passing through it. By training a simple machine-learning model on these sound patterns, the system can infer what the robot is doing in real time, detect where the robot is touching objects with great accuracy, and pinpoint contact locations rather accurately. It can also identify contact forces, materials, inflation

level, and even temperature – all using the same sensor setup, and it works reliably even in loud environments. **This “acoustic sensing” approach could simplify soft robotics by replacing multiple traditional sensors with a single, flexible, low-cost alternative that does not interfere with the robot’s design or movement.**

Wall, V., Zöller, G. & Brock, O. (2023). *The International Journal of Robotics Research*.*

A videogame shows us how to make good decisions in a group

When groups search for opportunities, they often face a familiar dilemma: think independently, or follow the crowd? A study suggests that the answer depends greatly on how rewards are structured.

SCIoI researchers Dominik Deffner, David Mezey, and colleagues placed participants in a realistic virtual world where they had to hunt for hidden “coins.” Players could either explore on their own or observe others and copy those who seemed successful. Some environments concentrated rewards in a few rich areas, while others spread them more evenly. The results showed a trade-off. Individuals who relied heavily on social information sometimes earned more for themselves by following others. But when too many people copied the same behavior, the group performed worse overall. Crowding around the same hotspots wasted effort and reduced efficiency.

A simple solution, however, changed the dynamic: collective incentives. When rewards depended on the success of the whole group, participants became less likely to blindly herd. They explored more strategically and adapted better to changing conditions. **The findings suggest that group incentives can reduce copying behavior and help groups make better decisions together.**

Deffner, D., Mezey, D., Kahl, B. et al. (2024). *Nature Communications*.*



* SEE “RESEARCH HIGHLIGHTS” SECTION (FROM P. 131) FOR MORE INFORMATION ABOUT THESE ARTICLES



Mice and cockatoos know a thing or two about intelligence

Learning is rarely just one thing. It blends movement, perception, memory, decision-making, and emotion – yet many animal experiments isolate only a single skill. In a SCIoI experiment, Manuel Baum, Oliver Brock, Alice Auer-sperg, and others **observed the behavior of Goffin’s cockatoos in an attempt to replicate some aspects of it in robots.** These birds can solve complex puzzles, and success depends on motivation, learning skills, and choosing actions together, and though we are far from understanding their complex behaviors, a step-by-step approach can bring us closer to our goal. In a different SCIoI experiment, members of the mouse lab gave mice a miniature lockbox, which is a multi-step mechanical puzzle that must be opened through a sequence of actions. The mice engaged with the task spontaneously and learned to solve it after only a few attempts. To understand how they improved so quickly, researchers combined multi-camera recordings, deep-learning behavior tracking, probabilistic analysis, and computational modeling. The mice first became better at physically manipulating the box’s mechanisms, only later adding a more strategic understanding of the correct action sequence. This shows that early success in mice is driven mainly by motor learning. Researchers are now redesigning the lockbox to better test how much reasoning mice truly use. **Experiments like these allow researchers to gather an understanding of natural intelligence and possibly create similar models that can work on robots. There’s still work to do – but each step is important.**

Boon, M., Andresen, N., Traverso, S. et al. (2024). *ICN 2024**

Baum, M., Rössler, T., Osuna-Mascaró, A. et al. (2024). *Adaptive Behavior*.*

Research Highlights

The Collective Brain

Why do we study collective behavior? Because swarms tell us a lot about how individuals work together, and because sometimes collective decisions are more efficient than those of individuals. Some of our studies even show that collectives closely resemble a nervous system, a brain of sorts. Here's why.

Self-organized criticality and the collective brain

What do the brain and a school of fish, or even a multicellular organism, have in common? They are both capable of efficient collective information processing, although each unit only has access to local information. In the brain, the stimuli from 86 billion neurons form the basis for information processing; in shoals, this is done via the decisions of each individual on how to move and interact with neighbors. However, little is known about how these biological systems manage to optimally bring together a multitude of individual pieces of information from different locations. According to a known hypothesis, the best performance of the brain lies at the border between order and chaos, in the so-called critical state. SCIOI researchers

have now obtained evidence for this hypothesis in a large school of fish. "Swarm behavior is often about information spreading like an avalanche. In this state, the individuals react maximally quickly to external stimuli with maximally effective information transfer," said PI Pawel Romanczuk. **"The resemblance between the fish's diving behavior and the brain's neuronal activity suggests some fundamental principles of collective computations, also giving clues as to how far the complex patterns displayed by animal groups can be interpreted as a 'collective mind' (also see p. 94)."**

Gómez-Nava, L., Lange, R. T., Klamser, P. P., Lukas, J., Arias-Rodríguez, L., Bierbach, D., Krause, J., Sprekeler, H. & Romanczuk, P. (2023). *Nature Physics*. *



Collective rule-breaking: When behavior becomes contagious

Rules shape much of our everyday lives, often unnoticed until someone breaks them. In an opinion paper by Jens Krause (biologist), Pawel Romanczuk (physicist), Anne Nassauer (microsociologist), and Marcel Brass (psychologist), they examine why this happens and how rule-breaking can spread through groups. The researchers focus on social influence and the cognitive processes that lead individuals to ignore norms. Central

Why some fish do the “Mexican wave”

Picture thousands of fish moving like a giant wave in the water, diving down and coming back to the surface. While humans engage in this kind of collective behavior for fun in stadiums when they perform *La Ola* waves, animals may do it to avoid getting eaten. A SCIOI-led team found that the “Mexican waves” collectively produced by a school of fish reduce its predator’s propensity to attack and hunting success.

The Baños del Azufre volcanic springs in Mexico, rich in hydrogen sulphide and poor in oxygen, are inhabited by sulphur mollies (*Poecilia sulphuraria*). The fish spend their time close to the surface to breathe, becoming targets of many different bird species. But when a bird approaches, the million-strong fish schools react collectively by diving down, each fish touching the water surface with its tail. From a distance, the school appears to be producing conspicuous waves. **“Because the waves are repeated and regular, we assume that they are more than a mere escape reaction,”** said David Bierbach. “Their aim might be to confuse the bird, but also a way to send a message: ‘We know you are there, don’t waste your time attacking us!’”

Doran, C., Bierbach, D., Lukas, J., Romanczuk, P., Krause, J. et al. (2022). *Current Biology*.*



Fish collectives: the bigger, the smarter

You see the predator fly towards you: should you flee or stay? For a single fish, that split-second choice can mean life or death. But in the wild waters of Mexico, sulphur mollies have a powerful advantage: numbers. SCIOI researchers found that the bigger the shoal, the smarter it becomes. In more than 200 real-life encounters, large groups didn’t just react faster to potential predators – they reacted better. They could tell the difference between a deadly attack and an innocent flyby with striking accuracy, avoiding both costly false alarms and fatal hesitation.

Even more surprising, these fish break a classic rule of decision-making: they don’t trade speed for accuracy. Instead, they gain both. In the largest shoals, nearly every real threat was detected correctly – and in record time.

How? Not by following a single leader, but through a kind of natural “swarm intelligence,” where information travels through the group like a living network.

The result reminds us that sometimes, thinking together beats thinking alone.

Pacher, K., Bierbach, D., Sevinchan, Y., Vollmoeller, C., Juarez-Lopez, A., Wolf, M., Romanczuk, P., Krause, J. et al. (2025). *Science Advances*.*

*** SEE “RESEARCH HIGHLIGHTS” SECTION (FROM P. 131) FOR MORE INFORMATION ABOUT THESE ARTICLES**

to their argument is social contagion: Behavior can pass from person to person, sometimes gradually, but sometimes through sudden, non-linear shifts that rapidly change crowd dynamics. To better predict collective rule-breaking, the researchers argue that psychology, microsociology, and mathematical modeling need to be combined.

In another study, researchers explored how group settings influence risk-taking using a virtual version of the Balloon Analogue Risk Task. Participants inflated digital balloons for rewards, knowing they could burst at any moment. They completed the task while surrounded

by computer-generated agents whose behavior ranged from cautious to reckless. **The findings showed that people took greater risks when more agents were active and when these agents took higher risks.** Even simulated social environments, the study suggests, can strongly shape human decision-making and provide an experimental tool to study group phenomena that are otherwise difficult to investigate experimentally.

Krause, J., Romanczuk, P., Cracco, E., Arlidge, W., Nassauer, A. & Brass, M. (2021). *Trends in Cognitive Sciences*.
Daneshi, A. & Brass, M. (2025). *Royal Society Open Science*.*

Research Highlights

Improving Robotic Vision

Intelligence and sensory perception are closely intertwined, and vision often serves as one of the primary foundations of intelligence.

How do we efficiently apply natural vision to robots? Here are our top discoveries in the field of vision.

Robotic eyes that work in Antarctica

Inspired by the remarkable efficiency of animal vision, scientists have long tried to give robots human-like eyes. One promising breakthrough is the event camera: a bio-inspired sensor that does not record full images like a normal camera, instead only detecting the pixels that change intensity, which allows machines to track motion with exceptional speed, precision and low power – even in poor lighting. In one SCIoI project, Friedhelm Hamann and colleagues developed the first event camera system that allows AI to follow arbitrary points even in darkness, glare, or high-speed motion. **This makes event cameras especially valuable for robots, drones, and self-driving cars, which must constantly judge movement and distance in real time.** And because of their low power expenditure, event cameras can also be useful in extreme environments, such as Antarctica. Working with Oxford University biologists, Guillermo Gallego and his team installed event cameras in a chinstrap penguin colony to study behavior during breeding season. Because penguins spend long stretches sitting still, the cameras save power and storage, yet instantly capture meaningful moments such as family interactions or disputes with neighbors. The project offers a clever new window into animal life.

Hamann, F., Gehrig, D., Febryanto, F., Daniilidis, K. & Gallego, G. (2025). *IEEE/CVF CVPR Conference*.
 Hamann, F., Ghosh, S., Martínez, I. J., Hart, T., Kacelnik, A. & Gallego, G. (2024). *IEEE/CVF CVPR Conference*.*

* SEE “RESEARCH HIGHLIGHTS” SECTION (FROM P. 131) FOR MORE INFORMATION ABOUT THESE ARTICLES



There's valuable information in that blur

When we move our eyes, our visual world doesn't simply “switch” between stable images. Instead, eye movements (known as saccades) rapidly sweep objects across the retina, leaving faint motion streaks. Are these streaks useful – or just an unavoidable side effect of moving



gaze? Richard Schweitzer, Martin Rolfs, and colleagues explored this using eye tracking and EEG while participants made rapid eye movements toward targets. During these saccades, targets either jumped abruptly or moved smoothly, creating continuous motion streaks. This allowed the researchers to isolate what the brain does with intra-saccadic motion streaks, i.e., the brief blur when the eyes are in transit. It turns out that these streaks are meaningful. When motion was smooth, participants corrected their gaze faster, making quicker follow-up movements. Brain signals also reflected the target's new position earlier – within about 50 milliseconds after the movement ended – especially in visual areas at the back of the brain. A computational model explains this: **The brain repurposes visual channels to encode motion, turning a blurry image into useful information.**

Schweitzer, R., Seel, T., Raisch, J. & Rolfs, M. (2025). *PLOS Computational Biology*.*

It's not what you see that matters to the eye: it's what it means to you

Every time you look around a room, your eyes are doing more than just “seeing.” They are constantly deciding where to go next – what to focus on, what to ignore, and what still doesn’t quite make sense. Vito Mengers and Nicolas Roth studied how this works in real-world situations, where things move, overlap, and compete for attention. Instead of treating seeing and eye movements as separate, they show they are tightly linked: What you see influences where you look, and where you look changes what you understand. According to their model, uncertainty drives attention. When something is unclear – like an object partly hidden behind another – your eyes are drawn to it to figure it out. When tested on real-world videos, the model closely matched how people actually scan scenes. It shows that attention isn’t guided only by what stands out visually, but also by what things mean. A car, a person, and a streetlight are not just pixels; they are meaningful units that structure how we look. **This brings us closer to understanding vision not as a passive snapshot of the world, but as an active, continuously unfolding process of exploration.**

Mengers, V., Roth, N., Brock, O., Obermayer, K. & Rolfs, M. (2025). *Journal of Vision*.*



Looking while moving makes robots see better

Imagine a robot that doesn’t just “see,” but looks at the world the way we do, by fixating on one object while moving. This is a simple but powerful behavior. By locking its gaze on a target, the robot can instantly estimate how far away it is and where nearby objects are, without complex calculations. Aravind Battaje and colleagues tested this on a robot equipped with a camera. When it focused on an object just 15 cm away, it estimated the distance with an error of less than 5 mm: about the thickness of a few coins. Even in cluttered scenes, when reaching for a cup behind a pile of objects, the robot could detect obstacles and adjust its movement. By combining distance and obstacle information, the robot can act in real time, successfully picking up objects of unknown size, even when something unexpected blocks its path. **In short, simply “looking while moving” makes robotic vision faster, simpler, and more reliable.**

Battaje, A. & Brock, O. (2022). *IROS 2022*.*

Vision helps robot swarms to move as a group

How do collectives move in such a coordinated manner? In 2020, Bastien and Romanczuk showed how collectives (e.g., flocks of birds, fish schools) can efficiently self-organize and coordinate their behavior with only minimal visual interactions between individuals. Inspired by this finding, David Mezey and colleagues developed a robot swarm that moves together using only onboard cameras and local visual cues, with no GPS, central controller, memory, or robot-to-robot communication. Inspired by animal groups, each robot reacts directly to what it sees rather than calculating

positions or distances. In experiments with ten ground robots and simulations, the swarm achieved coordinated motion, stayed cohesive, and avoided collisions even with limited vision and confined spaces. This overcomes common weaknesses of traditional robot swarms that depend on shared data or communication. **The system could improve search-and-rescue operations, agriculture, exploration, and adaptive robots in changing environments.**

Mezey, D., Bastien, R., Zheng, Y. et al. (2025). *npj Robotics*.*



Research Highlights

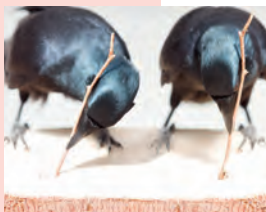
What is intelligence?

Defining intelligence is a hard task, maybe an impossible one, but we believe we have ignited the conversation.

Flexibility and learning from experience as signs of intelligence

In a variety of studies ranging from human infants to crows and bats, Alex Kacelnik and colleagues suggest that inherited knowhow, flexibility, learning, curiosity and generalization are key signs of intelligent behavior. In one of their studies, children who frequently combined objects during play tended to perform better in general problem-solving tasks, showing a link between general intelligence and tool use. This points to exploration and play as markers of broad cognitive flexibility in contrast with earlier generation ‘intelligent’ systems that excelled in some task by design, but did not have the breath of true intelligence. This does not exclude useful heritable predispositions. Nectar-feeding bats, for instance, live in complex environments with many fluctuating sources of food, and they successfully use exploration/exploitation skills to track which flower is most profitable at any given time. Combining animal research with robotics is crucial to infer what properties human-designed intelligent systems will need.

Rat-Fischer, L., Plunkett, K., von Bayern, A. & Kacelnik, A. (2024). *Journal of Experimental Child Psychology**
Chidambaram, S., Wintergerst, S., Kacelnik, A. et al. (2024). *Animal Cognition*.*



New discoveries in interdisciplinary research ethics

An important highlight of SCIoI research was the development of an ethics framework for research in the intelligence sciences. Developed by John-Dylan Haynes, Marten Kaas, and Christa Thöne-Reineke, this required bridging many different perspectives, ranging from philosophy of ethics, AI ethics and governance theory to concrete ethics frameworks as they exist for human and animal research. The outcome was an ethics review and monitoring process that allows to integrate these different disciplinary demands in this emerging and transformative new field. The framework is explained in more detail on p. 31.



Trustworthy, transparent robots



Our research on human-robot interaction examines several aspects of how people perceive and engage with the humanoid robot Pepper. In a pilot study on transparency and anthropomorphism, we were able to show that visualizing a robot's goals and behavior may increase (human) users' perceptions of the robot's agency. In another study on verbal collaboration, we showed that interaction with a speaking robot appears to facilitate conceptual processing through semantic priming (i.e., the activation of related concepts in memory). At SCIoI we also developed a social cognitive trust framework that enables our Pepper robots to evaluate human partners by combining cognitive load assessments with social cues such as gestures, allowing them to identify deceptive or unreliable partners. We also introduced the brain-based Turing Test, which uses implicit neural responses rather than explicit judgments to distinguish between human and artificial agents, offering a new approach to studying machine intelligence and human-robot interaction.

Pischedda, D., Kaufmann, V., Wudarczyk, O., Abdel Rahman, R., Hafner, V., Kühlen, A. & Haynes, J.-D. (2023). *32nd IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*.
 Mellmann, H., Arbutova, P., Kontogiorgos, D., Yordanova, M., Hafner, V. et al. (2024). *HRI '24 Companion*.
 Wudarczyk, O., Kirtay, M., Pischedda, D., Hafner, V. V., Haynes, J.-D., Kühlen, A. K. & Abdel Rahman, R. (2021). *Scientific Reports*.
 Taliaonak, V., Lange, A. L., Kirtay, M., Oztup, E. & Hafner, V. (2023). *32nd IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*.*

Deepfake smiles matter less

Deepfakes, i.e., realistic images and videos produced by generative AI, are becoming more common. However, it has been unclear how knowing if a face is real or fake affects our perception and emotional response. In a SCIoI study, Martin Maier, Rasha Abdel Rahman, and Anna Eiserbeck analyzed participants' reactions to smiling, angry, and neutral faces believed to be real or computer-generated. Findings reveal that AI-generated smiles are perceived as less intense, elicit weaker brain responses, and cause hesitation. In contrast, angry faces are equally threatening, no matter if real or fake. These insights have broad implications for societal interactions with deepfakes.



The study involved 30 participants and explored, via EEG technology, the effects of believing whether a face is real or fake on psychological and neural responses. **The study underscores the need for nuanced policies to navigate deepfake technology, emphasizing the understanding of its psychological and neural impacts.** Further research into other AI-generated content domains is essential to maximize benefits and address challenges posed by deepfakes.

Eiserbeck, A., Maier, M., Baum, J. & Abdel Rahman, R. (2023). *Scientific Reports*.
 Maier, M., Leonhardt, A., Blume, F., Bideau, P., Hellwich, O. & Abdel Rahman, R. (2025). *Social Cognitive and Affective Neuroscience*.*

* SEE "RESEARCH HIGHLIGHTS" SECTION (FROM P. 131) FOR MORE INFORMATION ABOUT THESE ARTICLES

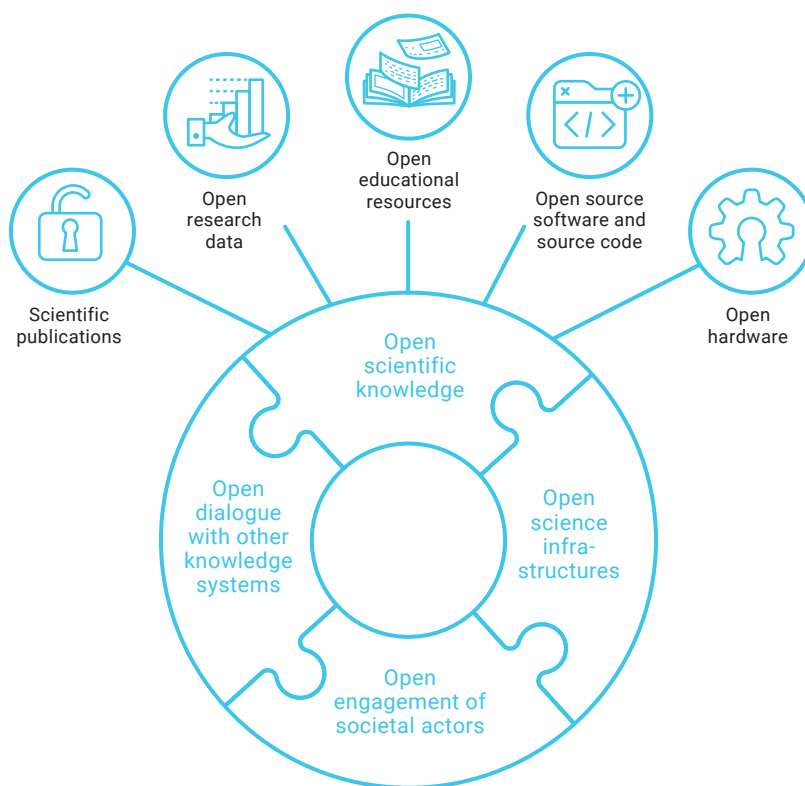


Acquiring behavioral data from large numbers of participants in public installations such as this one can be regarded as a form of public engagement in research.

Open Science... of Intelligence

Open Science is a set of practices aimed at making all aspects and outcomes of the research process transparent and accessible to the public. SClol has committed to applying the principles of Open Science to all its endeavors ever since its inception as a Cluster.

*BY MATHIS KAISER**



The concept of Open Science is based on a variety of recommendations: these include publishing the source code of the software used by researchers to produce and analyze research data, making all data and hardware designs widely available, and publishing articles free of charge to the reader. These practices increase the reproducibility of science, boost the impact of findings, and enable networks of researchers to answer complex questions, such as those about the principles of intelligence investigated at SCIoI. In the last few years, a few SCIoI projects, described below, have made use of different elements of Open Science.

Robotic hands

The RBO hand (created in the RBO Lab, which is closely partnered with SCIoI) is a soft robotic hand with pneumatic actuation. It is central

to SCIoI's efforts to develop a system that can autonomously and flexibly solve mechanical puzzles, the so-called "lockboxes" (SCIoI Project 17). Compared with other hands, created from rigid materials such as metal, soft hands make it easier to control grasping and manipulation, because contact with an object is stabilized automatically, which at the same time is a good example of embodied intelligence sparing computational resources.

Originally designed at the Robotics and Biology Lab (RBO), the hand was further developed in the context of SCIoI projects and has now reached its third generation. The system consists of a 3D-printed palm, silicone fingers flexing when pressurized, and valve banks with electronics to control air flow. Putting a wide range of Open Science principles into practice, the complete hardware design, including files for 3D-printing, production of electronics, and

This diagram, adapted from the UNESCO Recommendation on Open Science, details the elements of Open Science.

* Mathis Kaiser is a lab manager and member of the Research Data Committee at SCIoI. Previously, he completed a doctorate in Psychology about the role of neural oscillations in audiovisual perception.

a tutorial for assembly has been published along with a software stack to control the hand. After this resource was made available to the robotics community, it was soon adopted by researchers at ETH Zürich (Eidgenössische Technische Hochschule), and was distributed to partners at the Robotics Institute Germany.

Mouse lockboxes and big data

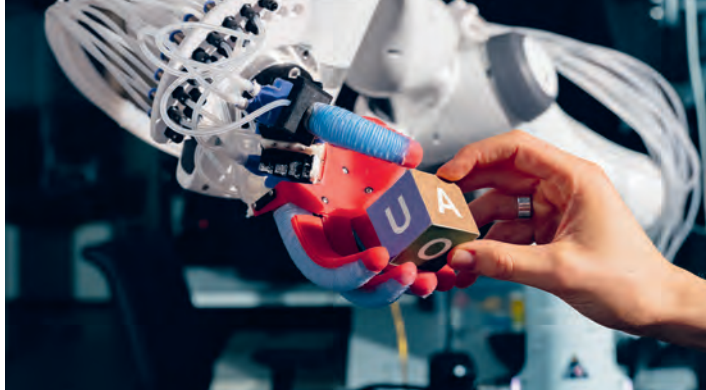
One cornerstone of the SCIoI research program is investigating intelligent behavior across species, allowing the identification of principles in well-known model organisms and controlled environments, and providing inspiration for building synthetic systems such as robots based on these principles. But there's a challenge: How can we create and automate the analysis of high-quality datasets on complex animal behaviors such as problem solving in mice?

SCIoI researchers tackled this challenge by publishing a large-scale video dataset of mice solving miniature versions of the lockbox, filmed from three perspectives for 120 hours and including human-annotated labels of actions performed by the mice (for example “bite a stick,” “touch a lever,” etc.). The work (SCIoI Project 3) was presented at the CV4Animals workshop at the 2025 Conference on Computer Vision and Pattern Recognition; an extended version, called Big Mouse Data (SCIoI Project 40), has now been commissioned and is currently under review at the International Journal of Computer Vision. This version will contain benchmarks for different automated behavior classification methods, and the dataset will be updated with keypoint coordinates for pose tracking.

Complementing the results of the mouse lockbox project, the Big Mouse Data project develops learning tasks closer to natural mouse



A mouse solving the mouse lockbox. Above right: Manipulations with the robotic arm.



NUMBERS AND SOURCES

behavior in a complex housing environment, and captures synchronized location tracking, video, and audio data. In order to make the large amounts of data accessible and comprehensible to other scientists, a database with detailed descriptions is currently being prepared for publication. It is important to note that the 3D-designs for the lockboxes and all hardware and software for the data acquisition are also open-sourced.

Modeling eye movements in dynamic scenes

To guide intelligent behavior in the real world, humans, other animals, and robots need to explore the visual scene by moving their eyes or cameras to locations of interest, from which they can then extract visual information (SCIOI Project 1). But the images they see are hardly ever still, especially when the agent's body is in motion. This makes it necessary to find ways to investigate eye movements in dynamic scenes. In order to simulate what they call “scanpaths” (visual paths), SCIOI researchers have developed a computational framework in the form of data, demonstrating that objects in the dynamic scene guide visual attention (also see article “Seeing with purpose,” p. 86).

In the spirit of Open Science, this framework, called ScanDy, has been open sourced and all data is shared on Open Science Framework. An interactive guide to using the software is also available. The modular nature of the framework allowed for easily extending it with a newly established, robotics-inspired principle of information processing in intelligent systems (the principle of active interconnections, see p. 64), paving the way for the integration of these insights into synthetic systems. ●

SCIOI's commitment to Open Science was formalized in a Research Data Policy, adopted by the SCIOI Executive Board in 2023, and came to fruition as researchers routinely published code and data along with their articles.

88 %

of SCIOI journal articles
are published as Open Access

76 %

of SCIOI papers include
Open Code and/or Open Data.

Examples of Open Source resources at SCIOI

Robotic Hand

Website: <https://www.tu.berlin/en/robotics/research-areas/infrastructure-and-tutorials/open-resources>

Code repository: <https://git.tu-berlin.de/rbo/robotics/rh3-stack-public>

Article: <https://doi.org/10.1109/TRO.2022.3156806>

Mouse Lockbox

Mouse lockbox dataset:

<https://doi.org/10.14279/depositonce-26085>

Mouse lockbox designs:

<https://doi.org/10.5281/zenodo.11143666>

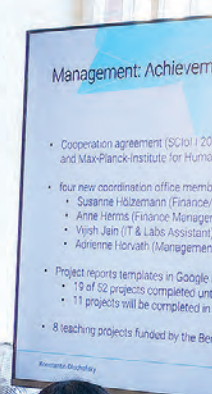
Article: <https://doi.org/10.1007/s11263-026-02908-x>

Eye Movements

Eye movement data: <https://github.com/rederoth/ScanDy>

Data repository: <https://www.doi.org/10.17605/OSF.IO/83XUC>

Article: <https://doi.org/10.1371/journal.pcbi.1011512>



Teaching the Next Generation

At SCIoI, we study intelligence as something that emerges through interaction between brains and bodies, individuals and collectives, natural and artificial systems. Between summer 2024 and summer 2025, that idea moved beyond research and entered the classroom.

BY MARIA OTT*

For about a year and with support from the Berlin Senate, nine teaching projects brought current SCIoI research into Master's-level courses. Doctoral researchers designed and led the seminars themselves, turning their own research questions into teaching formats. The result was a set of courses that asked how intelligence can be taught while it is still being explored.

The initiative also responded to a broader aim: strengthening Berlin's teaching landscape through new formats and closer collaboration between universities. The courses were hosted through Technische Universität Berlin and

open to students across institutions, linking disciplines such as computer science, psychology, biology, and robotics. At SCIoI, this created a rare opportunity to connect research and teaching in a context where formal teaching is usually not part of the Cluster's mandate.

The courses emerged from a competitive call for proposals. Doctoral researchers submitted ideas rooted in SCIoI's research themes, which were reviewed across disciplines and selected for funding. Over three semesters, nine courses took shape, covering topics such as robot learning, social intelligence, collective behavior, embodied intelligence, active sensing, and computer vision.

*** Maria Ott is a press and communication officer at SCIoI. She has a degree in Ethnology and Sociocultural Studies (MA).**



Left: a seminar room at the Scientific Networking Days retreat. Above: Jonas Frenkel gives a lecture.

“Research is no longer something distant or finished, but something students can engage with directly.”

Together, they reflected the breadth of the Cluster’s work. Some focused on how artificial systems learn and adapt. Others examined perception and behavior in biological and synthetic agents. Several explored how intelligence arises in groups, from animal collectives to robotic swarms.

In one course, students learned how to analyze behavior from video data, working with tracking methods, 3D reconstruction, and modeling approaches. In another, they explored robot learning through current research papers and discussions with invited experts. A seminar on artificial social intelligence examined how humans understand one another, and how machines might approximate these abilities, while also addressing ethical questions. Other courses combined modeling, programming workshops, and discussions on collective systems.

Despite their differences, the courses shared a common structure. They were built around discussion, reading, and direct engagement with current research rather than textbook knowledge alone. Many included hands-on elements, from coding to data analysis.

A defining feature of the program was the involvement of international experts. Researchers from institutions across Europe and the United States joined sessions as guest speakers, discussing their work directly with students. In many cases, students had already read related papers and could use the opportunity to ask questions and test their understanding.

These encounters shifted the classroom dynamic. Research was no longer something distant or finished but was something students could engage with directly. Many of the talks

were recorded and published online, extending the courses beyond the seminar room and contributing to SCIOI’s commitment to Open Science.

For the doctoral researchers who led the courses, teaching became part of their own development. Designing a seminar required them to structure knowledge, explain complex ideas clearly, and guide discussions across disciplines. In doing so, they also encountered the limits of their own understanding, often identifying new questions for their research.

For students, the experience offered a different perspective on science. They worked with data, built models, interviewed researchers, and discussed the implications of emerging technologies. In one course, the outcome was a published podcast series, bringing scientific conversations to a wider audience (see box, opposite page).

What remains is not only a set of courses, which can be watched online to this day, but a model in which research and teaching are part of the same process that is shaped by interaction, exchange, and the effort to understand something that is still unfolding. ●





Researchers attending a talk at SCIOl.



From seminar to public science

Out of all the courses, there is one that made the link between research and public communication especially clear.

In *Communicating Hot Topics in Intelligence Research*, by Nicolas Roth and Benjamin Lang, students learned the basics of science communication before conducting interviews with invited researchers and SCIOl scientists. The course brought together speakers from fields such as machine learning, neuroscience, and behavioral science, often attracting large audiences both in person and online.

Rather than ending with a written assignment, the seminar produced a public outcome: a new season of the podcast *Punching Cards, Intelligence Explained*. Students developed interview formats, recorded conversations, and translated complex research into accessible discussions.

This shifted the role of the classroom. While students were learning about science, they were also helping to communicate it, so that their work could become part of SCIOl's public output. This way, teaching, research, and outreach can intersect, and academic work can extend beyond the university.

The SClol Effect: Transforming Ideas

On 11 December, 2025, SClol PIs got together to discuss the future of SClol, new projects and horizons for an interdisciplinary intelligence research. What emerged from the many conversations at the meeting and thereafter is that the SClol experience had a strong, positive impact on everyone involved.



Ralf Kurvers

"SClol has shaped my research life and has changed my scientific thinking. I was truly inspired by the SClol example behaviors (see p.14), and I now always try to really connect to these great concepts in my research. What I mainly got from SClol is methodological expertise – next to the super nice crowd."



Christa Thöne-Reineke

"The interdisciplinary research and academic exchange within SClol led to the conception and successful application for funding for the 3RTG Graduate School, which is funded by the German Research Foundation and was launched in April 2026 (www.3RTG.de). I really couldn't have done it without SClol!"



Henning Sprekeler

"I am a theorist who looks at neurocircuits to understand how thinking works. At the Cluster I had a chance to really look at animals, mice to be exact, and see how crazily complex it all is. As a mechanistic person, just the complexity of behavior that I saw through SClol projects changed my view on my research."



Oliver Brock

"In my lab all want to use principles now, because they have realized that it's really useful!"

**Martin Rolfs**

"What I have learned from working in an interdisciplinary environment is that you have to change the way you communicate. If you want to explain something to your colleagues you need to take three steps back in your field to be sure that everyone understands. It's very interesting and also broadens your perspectives."

**Verena Hafner**

"Having the space to work across disciplines helped us understand the interplay between individual and social intelligence."

**Jens Krause**

"When we were in Mexico, we observed these kingfishers attacking the sulphur mollies, which caused them to make those crazy waves, then ended up going exactly where there were no waves, and we had a simple observational explanation for that. But then I talked to Martin Rolfs and Henning Sprekeler about this, and they made me realize that there is a lot more to it. Martin guided us to some specific vision papers, and we could calculate the bird's entire 3D trajectory based on what the bird can see and its perspective in general. Suddenly a whole world of observations opened up."

**Rebecca Lazarides**

"We were able to accomplish high-quality interdisciplinary work and connect educational psychology, computer science, and social robotics. This helped us better understand social dynamics in learning situations at the level of the learner, the interaction itself, and their consequences for motivational-affective and cognitive developments."

**Ralf Kurvers**

"I think we really managed the loop!"

Candidate Principles of Intelligence

The RBO soft robotic hand mimics the human hand and has a particularly efficient grasp.



From Recurring Pattern to Candidate Principle

Our initial goal at Science of Intelligence was to study intelligence in nature and to use this knowledge to design and create intelligent artificial systems. But then we started noticing some recurring patterns – and they looked very much like principles.

BY OLIVER BROCK AND SOLVEIG STEINHARDT*



A cockatoo uses a tool to solve a problem.

To understand the world around us, scientists build and test models that capture the essence of a phenomenon. There are two kinds: Descriptive models, which represent the measurable properties of a phenomenon, and mechanistic models, which go a step further by not only describing what can be observed, but explaining the processes that give rise to it.

When researchers identify recurring patterns in observations, these patterns can be understood as mechanistic models, or principles, i.e., general scientific laws that have numerous special applications across a wide field. When it comes to studying intelligence, these principles outline key properties relevant for intelligent artificial agents.

For each proposed principle, all of which are described in the next pages, SCIOI scientists have gathered empirical support across species, tasks, environments, and levels of abstraction, providing strong evidence that the principles hold true under a wide range of conditions. These mechanistic principles offer a powerful framework for understanding, characterizing,

and synthesizing intelligence. In a broader sense, they also help us see how the components of intelligence interact with and shape one another.

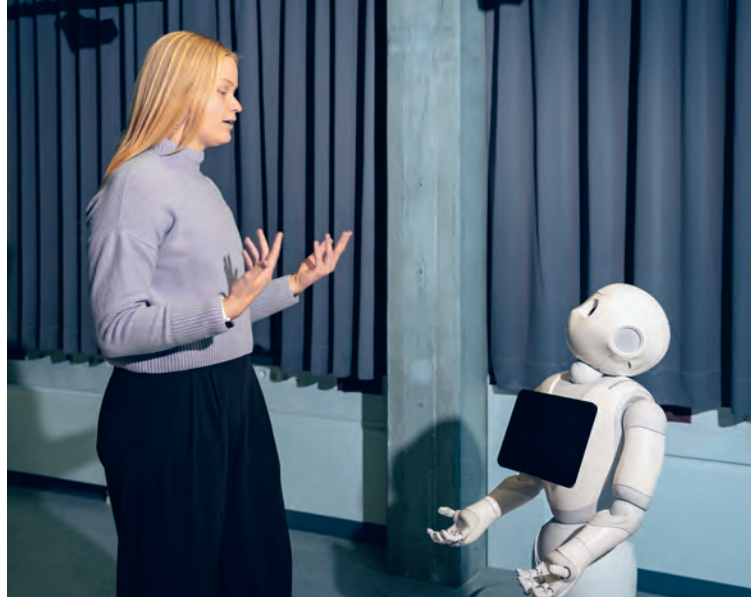
What is a principle?

In order to be considered a principle, a scientific law needs to possess certain properties. It has to represent a general, mechanistic regularity that applies to behavior across tasks, species, and contexts; it has to capture predictable relationships between body, environment, and action; and it needs to serve as a constructive guideline for designing intelligent agents. Based on these properties, we have found nine recurring patterns, or principles, of intelligence.

These candidate principles are meant to bring us closer to defining aspects of intelligence. It is important to note that they don't all have to be simultaneously part of a system for it to be considered intelligent. Some of the proposed principles (or "recurring patterns"), such as the principle of active interconnections, seem to be present in all intelligent systems, while others are not.

SCIoI's Candidate Principles of Intelligence

- Active interconnections
- Multiple computational paradigms
- Agent-environment coupling
- Adaptive representations
- Multimodality
- Multi-timescale computation
- Incremental assembly of capabilities
- Adaptation of structure
- Separating information into general and instance-specific



SCIoI researcher interacts with a Pepper robot.

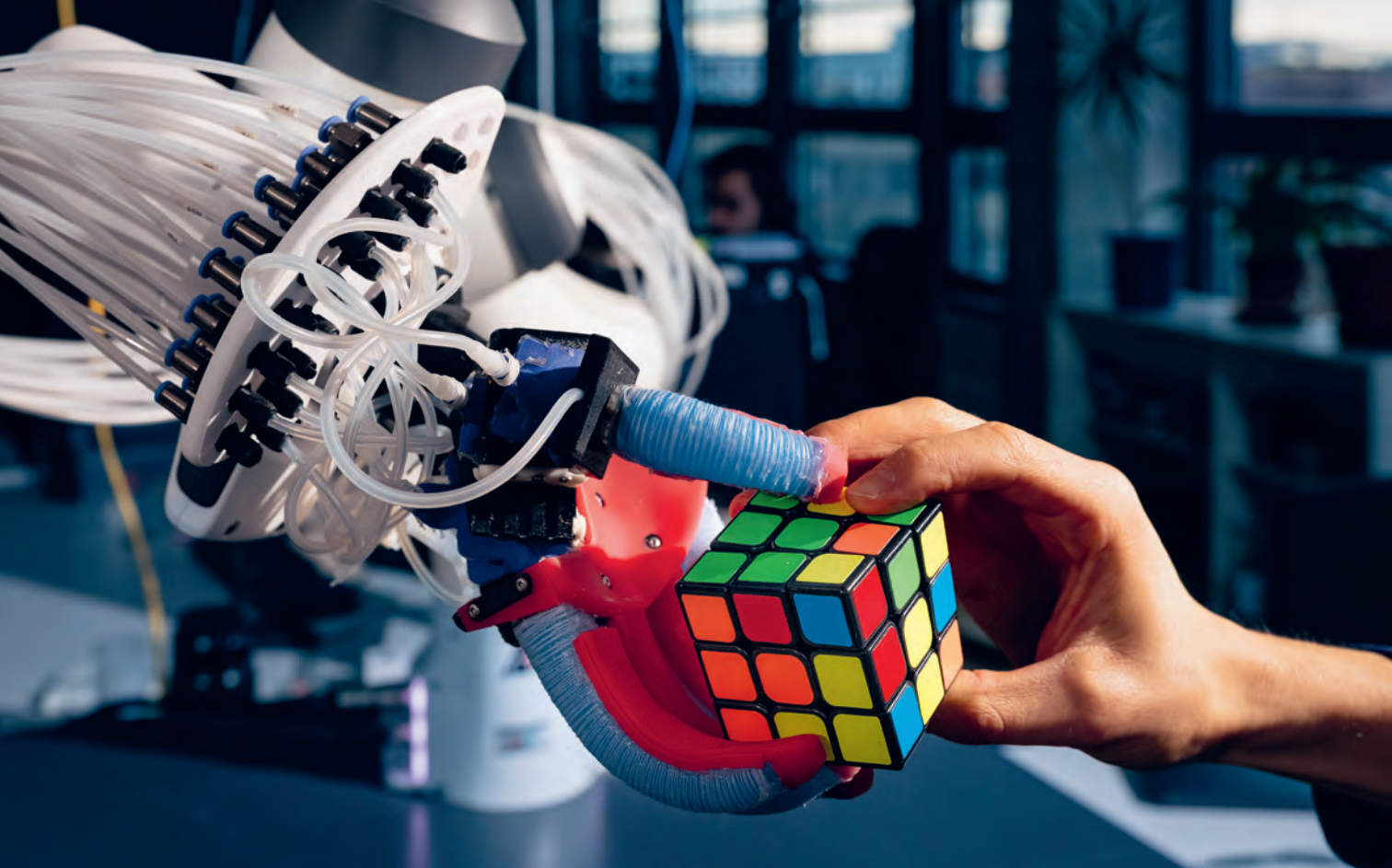
It is really not all that surprising; even literature (think: myths, tragedies, archetypes of heroes etc., that keep recurring), cooking recipes (think: roux turning into millions of different sauces by instantiation of a template), and music (think of stilemas, minimal units of music that help us define the musical style of a song) work that way.

Principles speed up research

What do principles do? They help us form hypotheses about how behavior is generated in specific cases, for example in particular species, tasks, cultures, or developmental stages. More specifically, their role is to narrow down the space of hypotheses we need to explore when conducting research. They act as conveniently encoded prior knowledge, letting us create hypotheses already backed by existing evidence.

We can think of principles as a toolkit, or building blocks of intelligence research. New tools are added as they are developed, while existing ones help researchers construct and test plausible explanations of intelligent behavior. Intelligence research either uncovers new principles or directly finds mechanistic explanations for intelligent behavior by using known principles to generate hypotheses that are highly plausible given prior evidence. Existing principles guide us toward the space of likely mechanistic explanations, and this speeds up intelligence research.

* Solveig Steinhart is a press and communication officer at SCIoI. She holds a degree (MSc) in Natural Sciences.



At SCIOI, we aim to build synthetic agents that are adaptable and able to solve problems.

The easiest way to find principles of intelligence

Because principles of intelligence show up repeatedly (across species, levels of complexity within an individual, social and collective behaviors, and at different developmental stages), we should be able to spot their effects in many situations. The best way to uncover them is by conducting comparative studies across all these dimensions. The more diverse the comparisons, the easier it is to spot patterns that recur. These recurring patterns point us toward likely principles, like a key that unlocks the secrets of intelligence. By looking across many scenarios, we increase the chance that what is shared among them reveals a core contributor to intelligent behavior.

Natural, synthetic intelligence – or no intelligence at all?

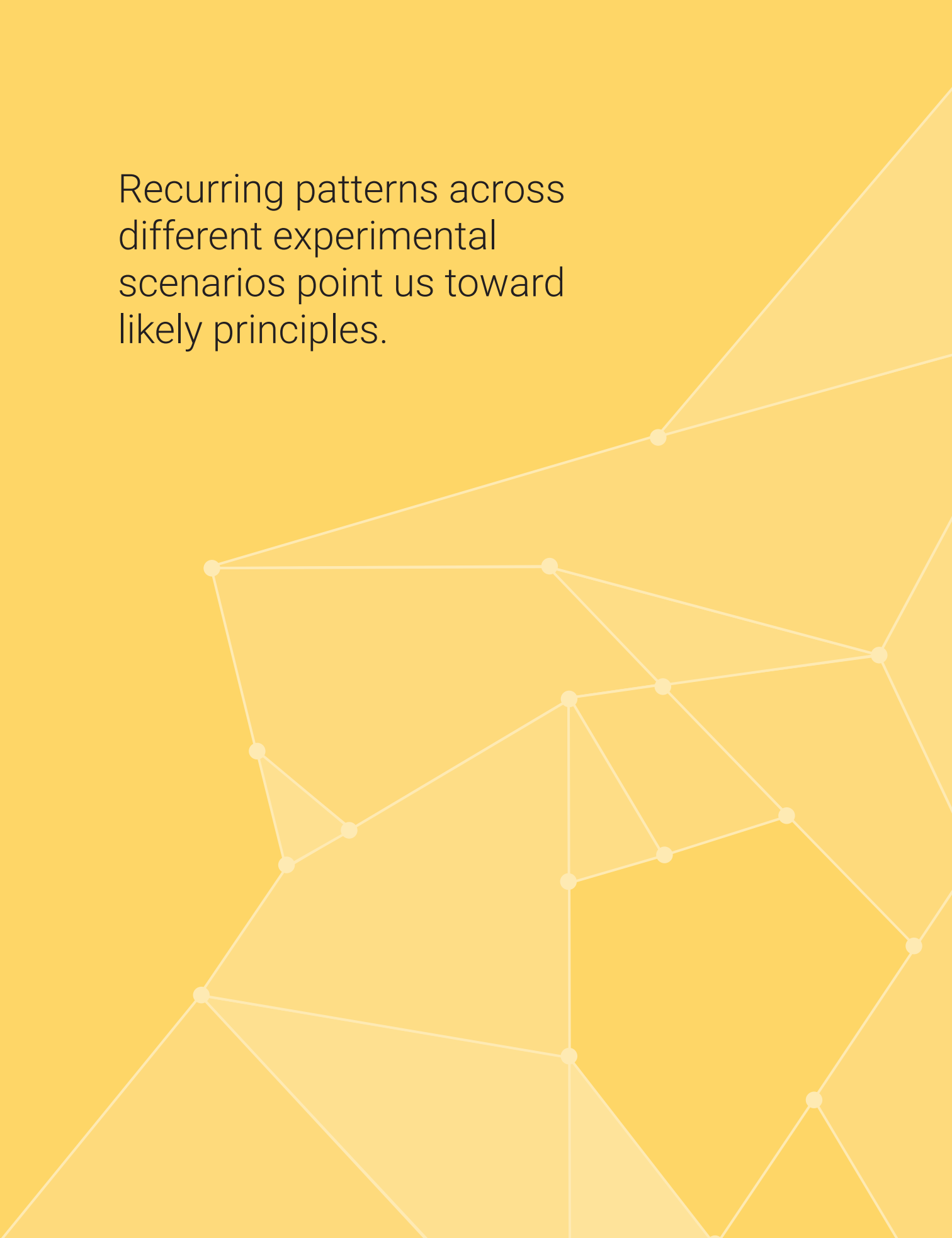
When we think of natural intelligence, we immediately think of animal brains: humans, dolphins, cockatoos, penguins – but even

mosquitoes and worms – creatures with nervous systems that naturally follow the principles of intelligence. Synthetic beings, like robots or machine-learning models, are inspired by this neural intelligence, and their cognitive behaviors can resemble those of natural systems.

But intelligence isn't limited to single brains. Consider a school of fish, a flock of birds, or a swarm of robots: The interactions between individuals create a “collective brain” that goes beyond any one member, sometimes leading to group decisions that are more accurate than those of individuals.

Many central questions remain open. For example, when is a system not intelligent? We would tend to say, when it fails to satisfy the principles above. Examples include cars, calculators, surveillance cameras, or thermostats – they follow fixed mechanical rules but lack the adaptability and problem-solving abilities that we believe are what constitutes intelligence. ●

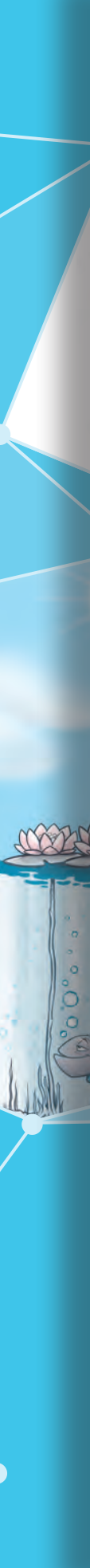
Recurring patterns across
different experimental
scenarios point us toward
likely principles.

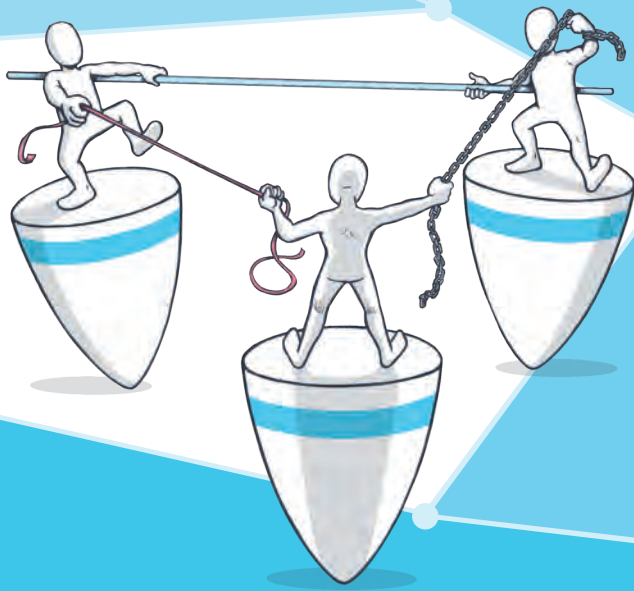


The Candidate Principles of Intelligence

Principles act as conveniently encoded prior knowledge, letting us create hypotheses already backed by existing evidences.

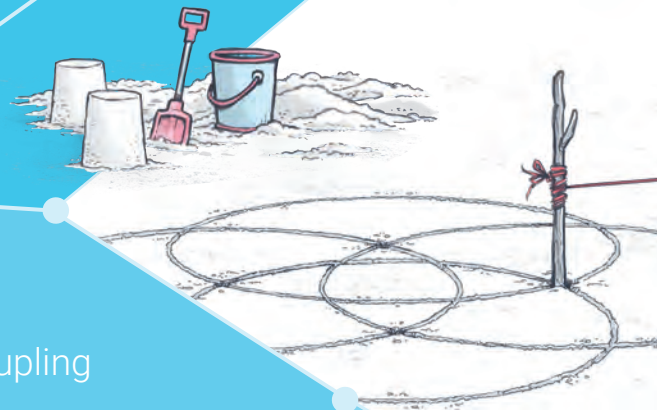






Active interconnections

The components of any intelligent system must communicate with each other via active interconnections. An interconnection is active if it shapes the information being passed in accordance with the state of the overall system. Just like the ropes keeping several balancing figures stable, as pictured above, these connections adjust whenever one part of the system moves (p. 64).



Agent-environment coupling

The generation of intelligent behavior is based on a flexible coupling of the agent to the environment. Through this coupling, the agent can create novel and task-related regularities that are in turn exploited during the generation of intelligent behavior. For example, if you draw a circle in the sand by tying a rope to a stick and use it as a compass, your interaction with the environment creates a reliable pattern that helps you solve the task more efficiently (p. 72).

Adaptive representations

Adapting one's representations of the world to the agent's environment, task, or goal facilitates behavioral flexibility. For example, in a busy market, the same scene is perceived differently depending on the goal: round objects stand out when searching for a football, while spotted patterns become more noticeable when looking for a spotted shirt (p. 76).



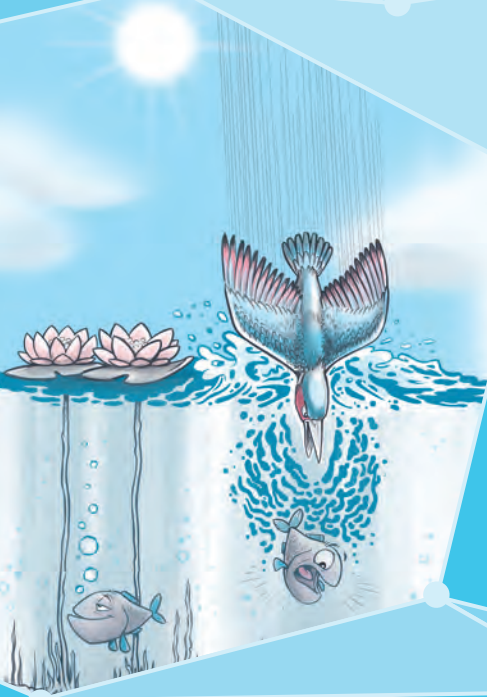
Multiple computational paradigms

The robustness and versatility of intelligent behavior results – at least in part – from the synergistic application of multiple computational paradigms. For example, a robot may identify an object computationally, while its soft fingers adapt mechanically to the object's shape, finding a stable grasp without calculating every movement (p. 68).



Incremental assembly of capabilities

This principle describes the ability of intelligent agents to efficiently find multi-faceted solutions to complex tasks via incremental assembly of solutions, much like children building with blocks: Simple structures are assembled first, then combined step by step into increasingly complex ones (p. 88).

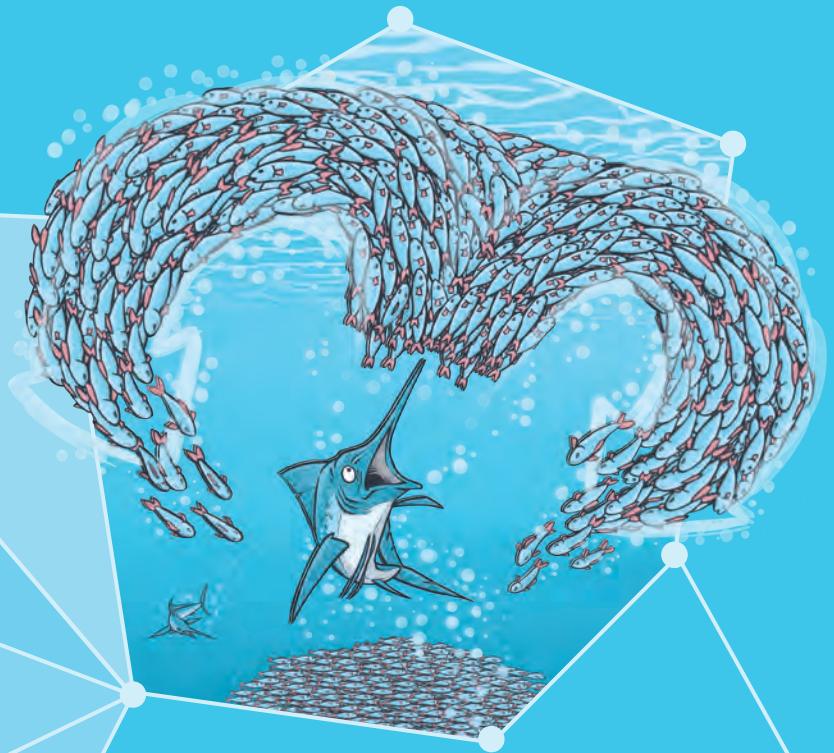


Multimodality

Processing information through multiple sensory channels is advantageous when operating in an uncertain and non-stationary world. For example, fish may respond only weakly to a shadow overhead or a disturbance at the water surface alone, but react strongly when both cues occur simultaneously, indicating a high likelihood of an attack by a fish-eating bird (p. 80).

Separating information into general and instance-specific

In order to effectively learn from experience and robustly generalize learned actions it is necessary to separate what is generally true from what is specific to a single situation. When an agent can separate these two types of information effectively, it becomes easier to learn from experience and apply knowledge to new cases, regardless of the details of the learning and acting process (p. 96).



Adaptation of structure

The principle of the adaptation of structure states that an intelligent system, to respond to long-term changes in its ecological niche or short-term environmental changes, may adapt its components to efficiently deal with such changes. This can be seen in fish swarms: When a predator approaches, the fish rapidly reorganize their formation, changing the structure of the collective to respond to the threat (p. 92).

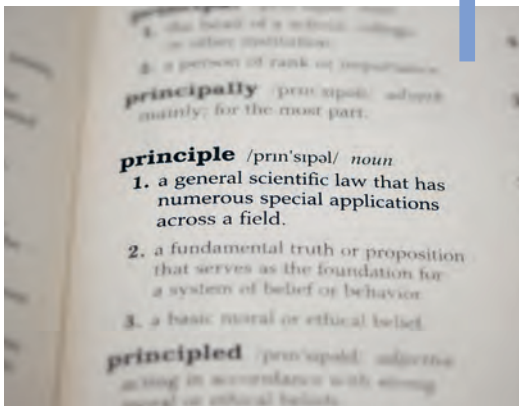


Multi-timescale computation

Adaptability to environmental change is a hallmark of intelligence. A mechanistic prerequisite for such adaptation is the presence of multiple timescales of computation to detect, track, and act upon changes in the environment. For example, a sequence of brief visual impressions can be integrated over time, allowing us to perceive a running horse rather than a series of separate images (p. 84).

5 Facts About Principles of Intelligence

Scientific research often produces vast amounts of data, models, and specialized findings. Yet across disciplines, scientists rely on something more compact to guide understanding: principles. Principles distill complex observations into simple, generalizable ideas that help researchers navigate uncertainty, structure models, and recognize patterns across seemingly different problems. They act as cognitive shortcuts – shaping how scientists ask questions, interpret results, and design new approaches.



What is a principle?

According to the Oxford College Dictionary, a principle is “a general scientific [...] law that has numerous special applications across a wide field,” describing “a fundamental quality determining the nature of something.” In its most general definition, a principle captures relevant and simple regularities; it is a fundamental, broadly applicable, and testable concept that describes how the natural world operates. Unlike specific scientific laws, principles function as overarching guidelines that help scientists explain phenomena, make predictions, and develop theories.





Principles summarize and simplify the research process

When you are conducting research, just the fact of knowing a certain principle can already influence your thinking, eliminate some possibilities as unlikely, or suggest directions to explore that might be deemed unconventional otherwise. The principle can serve as a mnemonic. It is easy to understand because it is a simple heuristic, a compact representation of knowledge one might otherwise not be aware of.

Some of the principles that changed the world

Here are some of the best known examples of principles that changed the course of research.

Archimedes' buoyancy principle, states that an object immersed in a fluid experiences an upward force equal to the weight of the fluid it displaces.

The principle of relativity, associated with Albert Einstein, states that the laws of physics are the same for all observers moving at constant velocity.

Werner Heisenberg's uncertainty principle, shows that a particle's exact position and momentum cannot both be known simultaneously.

Wolfgang Pauli's exclusion principle establishes that no two electrons in an atom can share the same quantum state, shaping atomic structure.

Daniel Bernoulli's principle explains how faster-moving fluids exert lower pressure, helping account for aerodynamic lift.



The famous story goes that Isaac Newton was inspired to formulate his theory of universal gravitation when he watched an apple fall from a tree.



Principles reduce the set of possible models we have to consider, and help find commonalities across studies

Principles can be used in two main ways when building scientific models: as building blocks that explain how something works (mechanistic components), or as guidelines that shape the model itself. When a model follows well-established principles, it is often more accurate and more widely useful. This is because those principles help narrow down which explanations are most likely to be correct, based not only on the data but also on what we already know about intelligent agents. Principles can also help researchers connect findings from different studies. By revealing common patterns, they organize existing knowledge and strengthen confidence in the principles themselves.

4



Principles give researchers a useful way to think about a problem

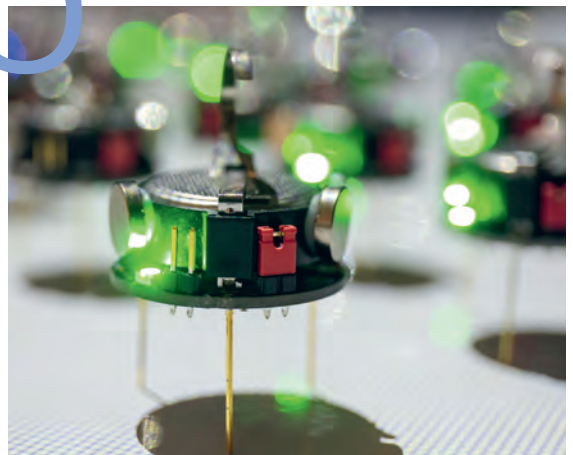
For example, the principle of active interconnections proposes two key elements: systems that estimate what is happening in the world, and the links or constraints between those systems. Researchers can then build models by identifying these elements in the area they are studying.

In this way, the principle provides a helpful starting framework, guiding researchers toward explanations that are likely to be productive.

5

Principle does not equal definition

Do principles define intelligence? The short answer is no – that's because they don't tell us what intelligence is, but rather why it works that way. Since the beginning of time, humanity has tried to define intelligence, but no single definition has been able to encompass all the different disciplines that make up intelligence. While a definition describes what something is rather than why it is the way it is, a principle is a recognized fundamental truth or law that guides how a system works. Principles are there to spot regularities that appear across disciplines, to explain how intelligence works across multiple components, and to possibly bring us closer to a more comprehensive description of this phenomenon.





A principle is a fundamental, broadly applicable, and testable concept that describes how the natural world operates. Unlike specific scientific laws, principles function as overarching guidelines that help scientists explain phenomena, make predictions, and develop theories.

Definition

The principle of [active interconnections](#) states that the components of an intelligent system (for example, the different areas in the brain, the information exchange among individuals in a flock of birds) must communicate with each other via interconnections that are active, i.e., which shape the information by adapting with the state of the overall system.





Active Interconnections

Intelligent systems, such as the brain or a flock of birds, consist of different components. These are connected with one another through interconnections that participate in information processing; these are flexible, adaptable, and able to combine information in novel ways depending on the situation. In other words, they are active, as opposed to the passive interconnections occurring in engineering systems such as a car or a washing machine, commonly regarded as non-intelligent, whose sparse and predetermined connections merely transmit data.

At Science of Intelligence, we have observed the presence of active interconnections in many instances of intelligent systems. The principle we derived from this observation represents a fundamental shift in how we conceptualize intelligent systems, maintaining that true intelligence emerges not just from sophisticated components, but from the rich, adaptive relationships between them.

These relationships function as “second-order components”: They operate not directly

on sensorimotor or environmental data, but on the components that process that data. This creates a system where the whole becomes significantly more than the sum of its parts, as the rich combinatorial possibilities of adjusting information flow between components allow for responses to novel situations that weren’t explicitly programmed. In essence, by using active interconnections, a system moves away from rigid, predetermined responses and gains the ability to adapt through the dynamic interplay of its components.

We believe that this recurring pattern, found in what are believed to be intelligent systems, forms one of the most fundamental elements of intelligence. *BY ARAVIND BATTAJE*

In this illustration, three figures are balancing on cones in order to keep stable. The three figures are actively interconnected, as their interconnections’ lengths and strengths adapt to the situation.

Just like the ropes keeping several balancing figures stable, as pictured above, these connections adjust whenever one part of the system moves.

“True intelligence emerges not just from sophisticated components, but also from the rich relationships between them.”



Vito Mengers adjusts the robotic arm.

Explaining the principle of *active interconnections*

The Robot that Didn't Need a Plan

When we carry out everyday tasks – opening a stuck drawer, or moving through a cluttered room – we rarely stop to plan each step in advance.

BY VITO MENGERS*

We act, see what happens, adjust, and continue. In robotics and AI, however, there is an expectation that complex sequential behavior requires explicit planning: You first model future states and then compute a sequence of actions ahead of time. In one of our projects, we deliberately removed planning altogether, and the system did not fall apart – a good example of the principle of active interconnections.

The project started with a simple question: Could a system solve multistep tasks without previously constructing an explicit plan? Rather than reasoning about imagined futures, the system continuously follows a gradient – a local direction of improvement – shaped by an internal landscape that reflects task structure and environmental constraints. You can think of

this landscape as terrain that shifts in response to what the system senses. At first, this seems simple. The concept of gradient descent, common in math and machine learning, is based on adjusting trajectories at each step and is usually associated with short-term optimization. The key difference here is that the landscape is not fixed. It is constantly reorganized by perception, feedback, and the changing state of the task. In effect, the issue is that the problem keeps changing while it is being solved. This ongoing restructuring produces behavior that looks a lot like planning, even though no explicit plan was ever formed. In experiments ranging from abstract block manipulation to real-world drawer interaction, the system handles multistep tasks, adapts to disturbances, and recovers from errors. If a drawer handle shifts unexpectedly or resists

* Vito Mengers is a doctoral researcher working at the intersection of robotics, perception, and computational models of intelligence.

movement, the system does not stop to recompute a strategy. Instead, the changing internal landscape redirects behavior in real time. What looks like error correction is simply part of the same ongoing process that produced the action, and what makes this work is not gradient descent alone, but the way information moves through the system.

This is an example of what we call “active interconnections”: connections

that do more than pass information along – they actively reshape it in response to the state of the system. In this project, those interconnections allow a fundamentally local process like gradient descent to contribute to tasks that appear to require long-term foresight. The system behaves as if it anticipates structure because the relationships between its components are constantly encoding and updating that structure as the situation unfolds.

The project itself was guided by the hypothesis that actively mediated interactions could support extended action, not just perception. Viewing the system this way influenced design decisions from the beginning, encouraging architectures where sensing, task constraints, and control continuously inform one another. In that sense, candidate principles do more than describe observed patterns; they can serve as working hypotheses that guide exploration toward new kinds of behavior. Similar interconnections are essential in perception of ambiguous input. Here, the same idea extends into action. Sequential behavior does not arise from a separate planner issuing commands to lower-level modules. Instead, behavior unfolds through the ongoing reorganization of relationships linking sensing, task structure, and movement. The boundary between perception and control becomes less rigid; both are part of the same evolving process.

This shift has practical implications. Traditional planning systems often rely on clearly separated components and explicit

contingency handling. A dynamically mediated system, by contrast, does not need to enumerate every possible failure in advance. Robustness arises from maintaining flexible interactions that remain sensitive to context. More broadly, this suggests that intelligent behavior may

depend less on elaborate symbolic foresight and more on how a system organizes information flow between its parts. When interconnections

actively participate in computation, relatively simple mechanisms can support surprisingly rich behavior.

The reception of this work – recognized by the planning and control community – highlights how counterintuitive this perspective can seem. Removing explicit planning might appear like a step backward, yet the resulting system shows that intelligence can emerge from carefully structured interaction and response to changing conditions rather than centralized deliberation. The project is less about replacing one algorithm with another and more about reconsidering where intelligence resides – and we believe it resides in the system’s active interconnections. ●

“Active interconnections
reshape information
rather than pass it along.”



A robotic arm solves a puzzle based on shape and color.



Definition

The principle of **multiple computational paradigms** suggests that the robustness and versatility of intelligent behavior results – at least in part – from the synergistic application of multiple computational paradigms.

Multiple Computational Paradigms

At its most basic level, computation means receiving inputs, processing them, and generating outputs according to specific rules or operations. Your brain does this constantly: it takes in sensory information (inputs), processes it through neural pathways, and produces thoughts, decisions, or actions (outputs). From this perspective, one might think that understanding the brain would unlock intelligence in its entirety – end of story.

However, that view misses a crucial point: all species on Earth have evolved as embodied agents, physically interacting with their environments. But our brain isn't touching the world, you might object. In 1960, anthropologist Sherwood Washburn wrote in *Scientific American* that “the modern human brain came after the hominid hand.” It's a bold claim, yet it underscores the idea: Intelligence is not just a product of the brain. What other computations contribute to its emergence?

Humans perform neural computation in their nervous systems, but they also perform mechanical computation through their bodies. When grasping an object, the brain identifies the target, triggering movements that bring the hand toward it. Each computational system – neural and mechanical – tackles the sub-problems it is best suited for. Together, these layers produce highly robust, adaptable behavior: the very essence of intelligence.

BY ADRIAN SIELER



A robot may identify an object computationally, while its soft fingers adapt mechanically to the object's shape, finding a stable grasp without calculating every movement.

Explaining the principle of
multiple computational paradigms

A Body That Knows

Within our Cluster, researchers use soft robotic hands to study grasping and fine manipulation. These hands are much more than practical tools for picking up objects: They help scientists find new regularities in intelligent behavior and identify candidate principles of intelligence. One of these is the candidate principle of multiple computational paradigms: the notion that intelligence can emerge from the interplay of different forms of computations, for example neural processing combined with the mechanics of the body itself.

BY ADRIAN SIELER*



A SCIOI researcher programs a Nao robot for an experiment.

Up until a few years ago, the dominant approach in robotics was to build robots using rigid, well-understood mechanical parts. But things have changed, and these days it can be argued that there is a new discipline of building robotic systems from soft, adaptive, and deformable materials, and this marked a major shift in robotics. This field is highly inspired by biological systems. In this shift, the robot's body is treated as an active contributor to intelligent behavior.

There are multiple ways of “thinking” at play here, but the bottom line is that successfully using soft robotic systems means using digital control to exploit the body's own natural, mechanical intelligence. Let's examine a simple task such as picking up an object, a natural task for humans. For a robot built from rigid



Adrian Sieler
working with the
robotic hand.

“Neural computation
doesn’t only happen in
our brain. It also
happens in our hands.”

materials, however, this task needs slow and precise movements, because any unexpected contact with a table or an object might cause damage. In a sense, the system is effectively afraid of contact altogether. Yet this creates a paradox: interacting with the world is all about making contact, so what does the mechanical intelligence of a soft hand actually unlock?

Going back to humans, let’s consider how we pick up a small object from a table. We first touch the table around the object with our fingers, then slide them toward the object until we have it secured from all sides. Our soft human hand conforms to the environment without us having to think about it. In short, the body itself is performing a kind of mechanical computation. By building robots with soft hands instead of rigid ones we can replicate these strategies. We can drive the hand directly into contact with the environment without

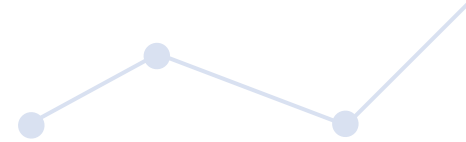
risking damage, because it passively adapts to the surface. This allows for guided finger motion without relying on precise sensors, detailed models or complex perception.

If we fully embrace these two sources of intelligence (neural and mechanical) and understand that they can work simultaneously, robotics becomes a challenge of co-designing the body and the digital controllers steering it. In my research, whenever a task does not work, I first think about how I can change the hand to make the digital programming simpler. This has led to making the silicone finger pulps softer and stickier, or smoother and thinner. It even led to the design of a second thumb, which is very useful for securing and manipulating objects within the hand.

To replicate the natural intelligence of humans or animals, we need to take the mechanical intelligence of the body seriously. Trying to solve these problems using only digital computation leaves us with a much harder, and maybe impossible, task. This is why we think that the simultaneous use of multiple computational paradigms is a good indicator of intelligent behavior. ●

* Adrian Sieler
is a doctoral
researcher
working in the
field of robotic
manipulation.

Agent-Environment Coupling



The candidate principle of agent-environment coupling derives from the idea that intelligent behavior comes from the way an agent (a person, animal, or robot) interacts with its environment. Intelligence isn't just inside the agent; it emerges from the ongoing relationship between the agent and the world around it. Rather than treating the agent as separate from its surroundings, this principle highlights how intelligence arises from the continuous, flexible, and dynamic interactions that happen as the agent moves, senses, and acts in the world. In this view, the world actively shapes and is shaped by the agent's behavior.

Both the agent and the environment are physical entities, so their interactions follow the laws of physics. Within these interactions, we can find regularities – consistent and repeatable patterns linking the states of the agent and the environment. Some of these patterns exist naturally, such as gravity pulling objects downward or the way edges define the shapes of objects we see. Others persist across different contexts and environments, and agents that recognize these structural regularities can reuse them as reliable shortcuts for future behavior. But agents can also create new regularities by interacting cleverly with their environment. For example, to draw a perfect circle in the sand, you might tie a rope to a stick and use it as a compass. This creates a reliable relationship between your movements and the resulting shape – a pattern that did not exist before. In this sense, intelligent agents do not just follow the rules of the world; they can invent new patterns that make future actions more predictable and controlled.

The key idea is that to understand or produce intelligent behavior, we should focus on the combined agent-environment system rather than what happens only inside the agent. Intelligence emerges in the space between agent and world, in the structure of their interactions. By studying these interactions, we can see how behavior that looks smart or adaptive arises naturally, and how even simple agents can produce complex outcomes through repeated engagement with their environment. The more attention we pay to the patterns and regularities in this shared space, the clearer it becomes that intelligence is a property of the interaction itself – not just the agent.

BY SOLE TRAVERSO*

* Sole Traverso is a doctoral researcher working in the field of computer science.

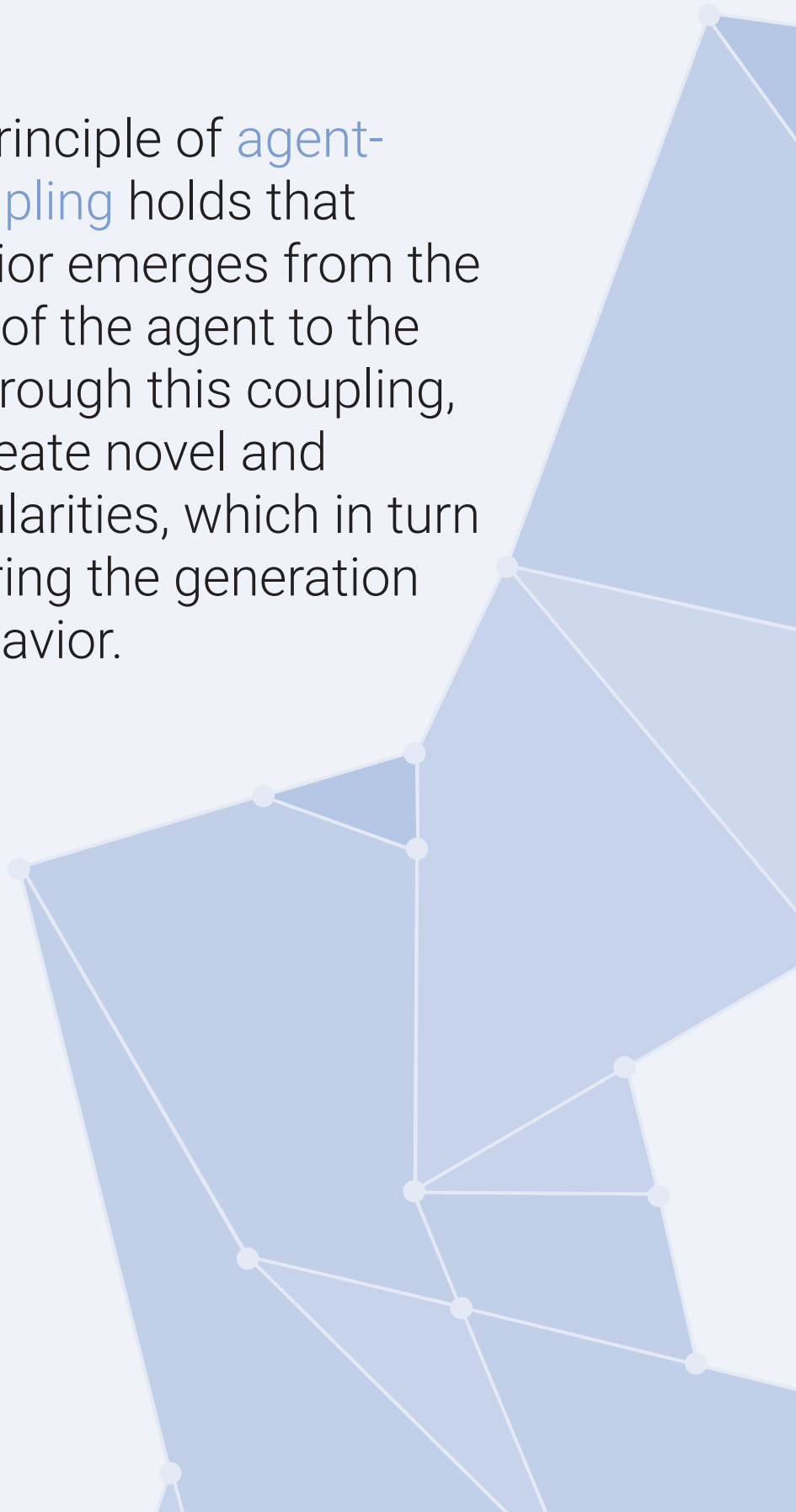
“Intelligent behavior is closely connected to how the agent (person, animal, robot) interacts with its environment.”



If you draw a circle in the sand by tying a rope to a stick, using it as a compass, your interaction with the environment creates a reliable pattern that helps you solve the task more efficiently.

Definition

The candidate principle of **agent-environment coupling** holds that intelligent behavior emerges from the flexible coupling of the agent to the environment. Through this coupling, the agent can create novel and task-related regularities, which in turn are exploited during the generation of intelligent behavior.



Explaining the principle of *agent-environment coupling*

The World Does All the Work

Distance is something you usually think of as measured: by a tape, by sonar, by stereo eyes comparing two images. But there is another way to know how far something is, and your body uses it constantly without telling you. As you move past an object while keeping your eyes fixed on it, your eyes must rotate – and that rotation, paired with your own motion, is the distance. A robot with a single-camera built around this fact can do things that elaborate vision systems struggle with.

BY ARAVIND BATTAJE*

* Aravind Battaje obtained his PhD in robotics and works on robotic interactive perception.

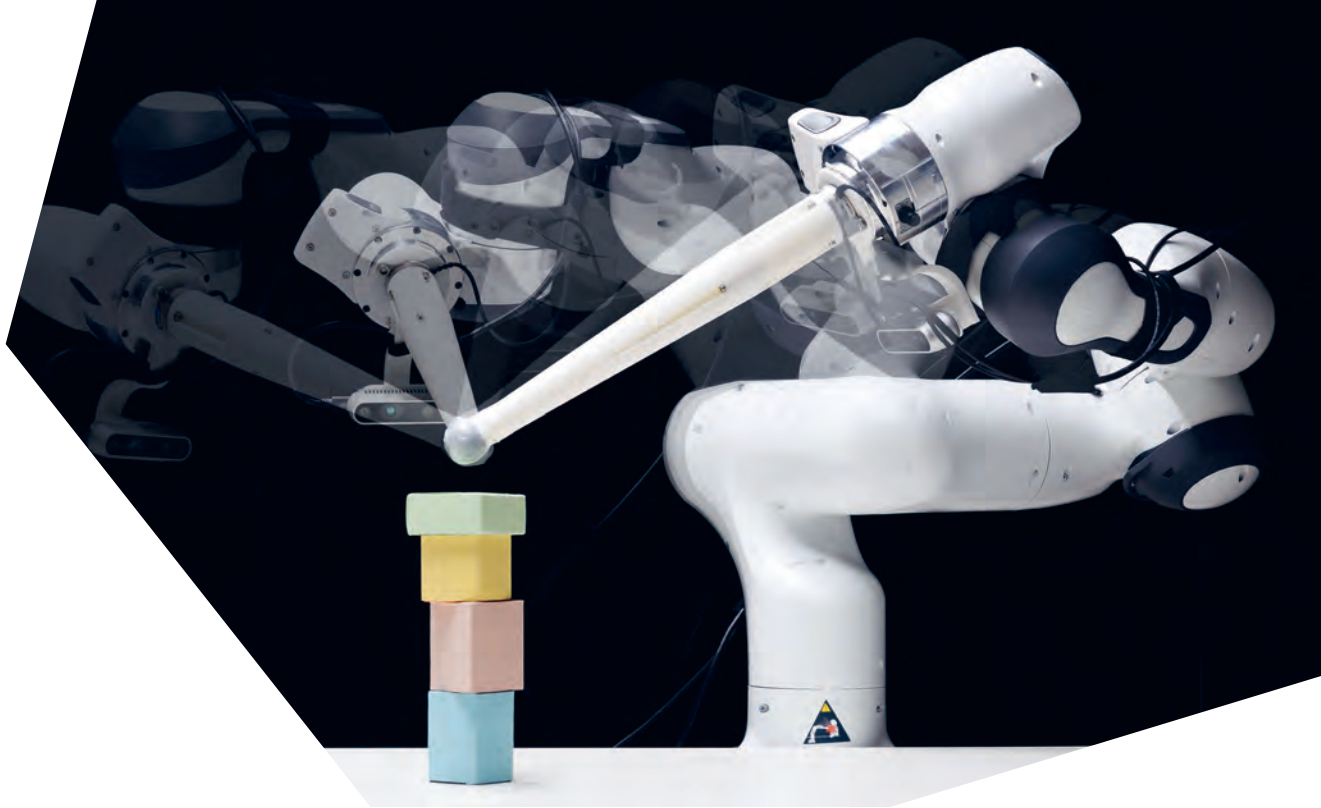
This habit of locking your gaze on one object while you move is called fixation. Animals do it constantly. When you walk across a busy street toward a friend, you fixate on them. Your body sways, the crowd shifts, your head turns, but your eyes hold the friend steady in your visual field. You don't even think about it.

During fixation, your eyes must rotate to compensate for your own movement, and the closer the object, the more they have to rotate. Try it. Lock your gaze on the lamp on your desk and slide your head a few centimeters sideways. Your eyes will swivel sharply. Now do the same with a building across the street. They will barely move.

This is not a quirk of biology but a strict consequence of geometry. As you slide sideways while keeping a point centered in your vision, you are tracing a circle around the point. The radius of that circle is the distance between you and the point. Distance, in other words, is built into the shape of your own motion.

This realization motivates a different way to build robots. To appreciate it, consider how robots usually handle the problem of measuring distance. Most use stereo cameras, LIDAR, depth sensors, or learned vision models that infer 3D structure from images. These methods are powerful, but they still have their weaknesses. They demand specialized hardware or large amounts of training data, and they tend to fail in difficult situations such as when they encounter glass surfaces, mirrors, blank walls, or objects the system has never seen.

The robot we built uses fixation. It has a single ordinary camera, attached near the gripper of a robotic arm. It picks an object to look at, and it moves the arm slightly from side to side while keeping the camera locked on that object. From the rotation of its own camera, paired with the speed at which it is moving, it reads the distance to the object directly. The object's appearance is barely involved. But when the robot focused on an object just 15 cm away, it estimated the distance with an error of less than 5 mm. At several meters, the error



“The world cooperates
because it is structured.”

The robot uses its
own motion to
measure distances
while staring fixedly
at an object.

is still less than a sixth of what a comparable system produced without fixation. All of this from one ordinary camera and a careful way of moving.

There is a second useful property of gaze fixation. While fixating, anything closer than the target drifts across the visual field in one direction, and anything farther away drifts in the opposite direction. The fixated object stays still. To know whether some other object in the scene is in front of or behind the target, the robot does not need to measure its distance. It only needs to notice which way that object is moving across the camera frame.

This sounds like a small thing, but it lets the robot handle situations that defeat conventional vision. A clear glass cylinder, for instance, is almost invisible to most vision systems, because nothing in its appearance distinguishes it from the background. But as the robot moves, the cylinder still drifts in the direction that means “closer than the target.” That is all the robot needs. It steers around it.

Step back for a moment. The robot is not smarter than its competitors. Its camera is not sharper. Its computer is not faster. It has not learned from a million examples. It is doing less computing, not more. Other systems do that computing internally: they build depth maps, compare image features, match against learned priors. The fixating robot does almost none of this. The work has moved out of its processor and into the geometry of the world, made accessible by the way the robot chooses to move.

This is an example of the candidate principle of agent-environment coupling. Intelligent behavior does not have to live entirely inside an agent. It can live in the loop between the agent and its environment. By moving in a way that makes the world easier to read, the agent shifts part of the work onto the world. The world cooperates, because it is structured. Geometry, dynamics, and the regularities of physics are reliable enough that an agent engaging with them properly can let them carry some of the load. ●



Definition

According to the principle of [adaptive representations](#), behavioral flexibility is facilitated by adjusting the representations of world state to the agent's environment, task, and goal. Adaptive representations ensure that a system represents aspects of the world that are most relevant to behavior in a way that is most conducive to generating that behavior.



A line graph with three data points connected by lines. The first point is at a low level, the second point is at a high level, and the third point is at a medium level.

Within the human brain, where specific neurons and neuronal ensembles code specific pieces of information, this coding is remarkably adaptive. Neurons and ensembles emphasize

BY RASHA ABDEL RAHMAN

“Intelligent entities represent reality in a flexible way. For example, the same face may appear angry or friendly depending on our previous experience and ideas, or on our goals.”

Explaining the principle of *adaptive representations*

Context Changes Meaning

Context and previous experience can change how we perceive and make sense of our visual environment. Through EEG technology, we track rapid brain activity, which allows us to see when expectations shape perception – sometimes even before a stimulus is consciously recognized. To understand this process, it is useful to look at the candidate principle of adaptive representations, which explains how intelligent systems dynamically reshape their internal representations of the world.

BY RASHA ABDEL RAHMAN*

One thing we know about intelligent systems is that they do not store fixed pictures of reality: they continuously reshape their internal representations using past experience, uncertainty, and whatever the current task is demanding. Instead of encoding all features equally, they dynamically re-weight relevant factors, constructing task-dependent approximations of the world rather than a single objective description. These very facts are the bottom line of the principle of adaptive representations.

To better explain, it is important to say that everything we perceive and do is influenced by many different aspects at the same time. For example, when I look at a cup, what reaches my eyes depends not only on the cup itself, but also on the lighting, the angle I am looking from, and even the position of my own body.

* Rasha Abdel Rahman (pictured right) is a Principal Investigator at SClol working in the field of psychology.





Our expectations, knowledge, and prior experiences shape the perception of facial expressions.

Because all these influences are mixed together, the brain never receives a perfectly clean description of the world.

In an ideal situation, we would be able to separate these influences completely. We could know exactly which part of the signal comes from the object's shape, which part comes from the lighting, which part comes from distance, and so on. A representation like this – where each factor is separated and does not interfere with the others – is called a disentangled representation, but such perfect separation is not realistic.

Instead, the information we get from the world is mostly incomplete, noisy, and ambiguous, and the brain (or any intelligent system) can only build an approximation of reality, maybe a close guess but never an exact copy of it. An example of this is hearing speech in a crowded room. Even when parts of words are masked by noise, your brain fills in the missing pieces using context and expectations.

For a specific task, some guesses are better than others. A representation is “good” when it separates the factors that matter for the task more clearly than the ones that do not. But what matters changes from situation to situation. Because of this, an intelligent system must constantly adjust how it represents the world. In other words, its representations must be adaptable.

One way this adjustment happens is by changing how important different features are treated. The system gives more influence to

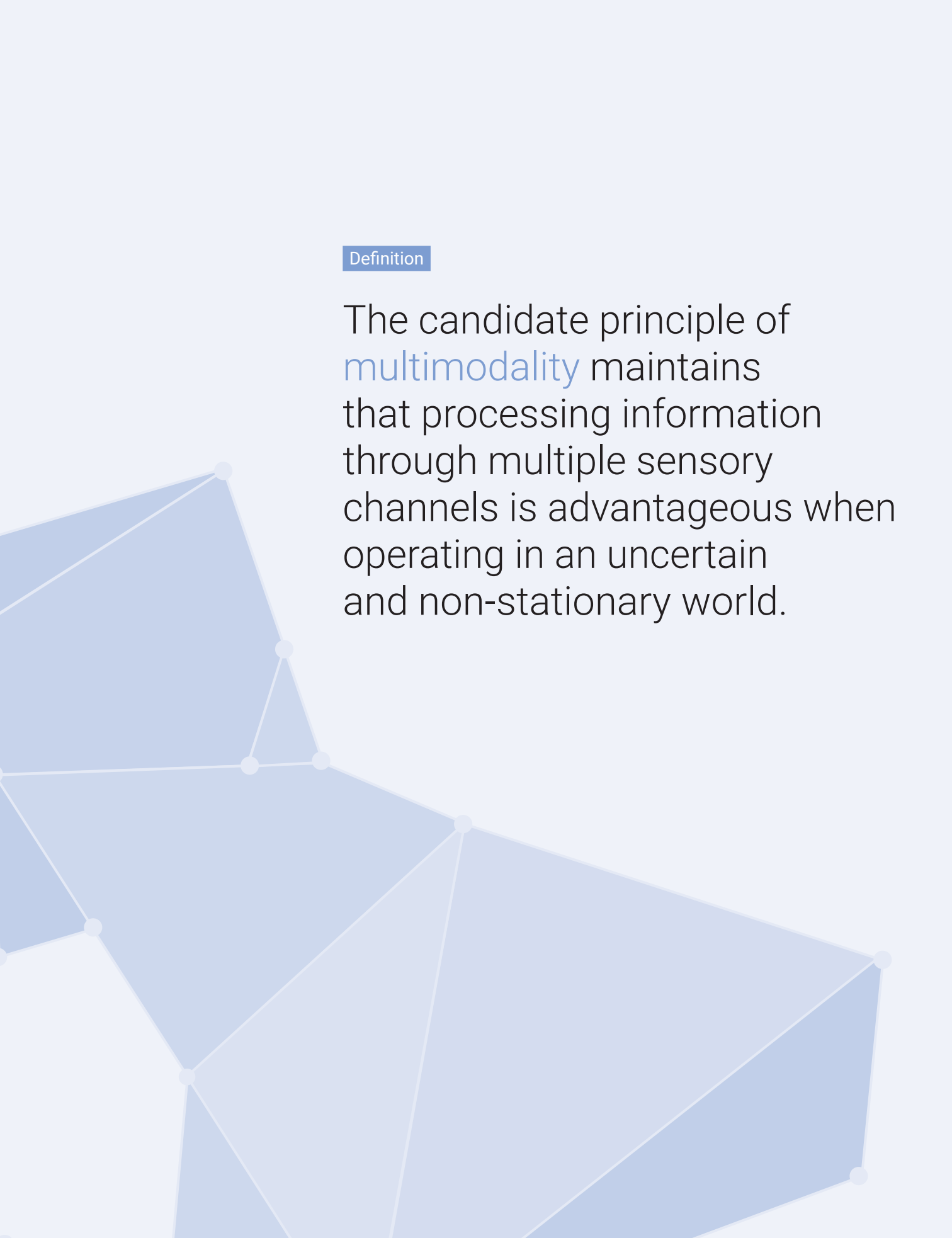
useful information and less influence to irrelevant information.

For instance, when you want to pick up a cup, the shape and size of the cup matter a lot, while its color matters very little. So the system increases the importance of shape and weight and lowers the importance of color. Changing these importances also changes how signals travel inside the system – some internal pathways become more influential, and others less. While adaptive representations are a crucial property of individual and social intelligence, how much explanatory power they hold for collective intelligence is still an open question. ●

“The information we get from the world is mostly incomplete.”

What would a non-intelligent system do?

In order to most efficiently understand this candidate principle, it is useful to make a comparison with non-intelligent entities, which in this case could be exemplified by engineering artifacts such as a face recognition camera. The camera will recognize the face and its features, but will not be able to adapt its interpretation to its previous experience, or give bigger weight to certain features based on its memory of the task.

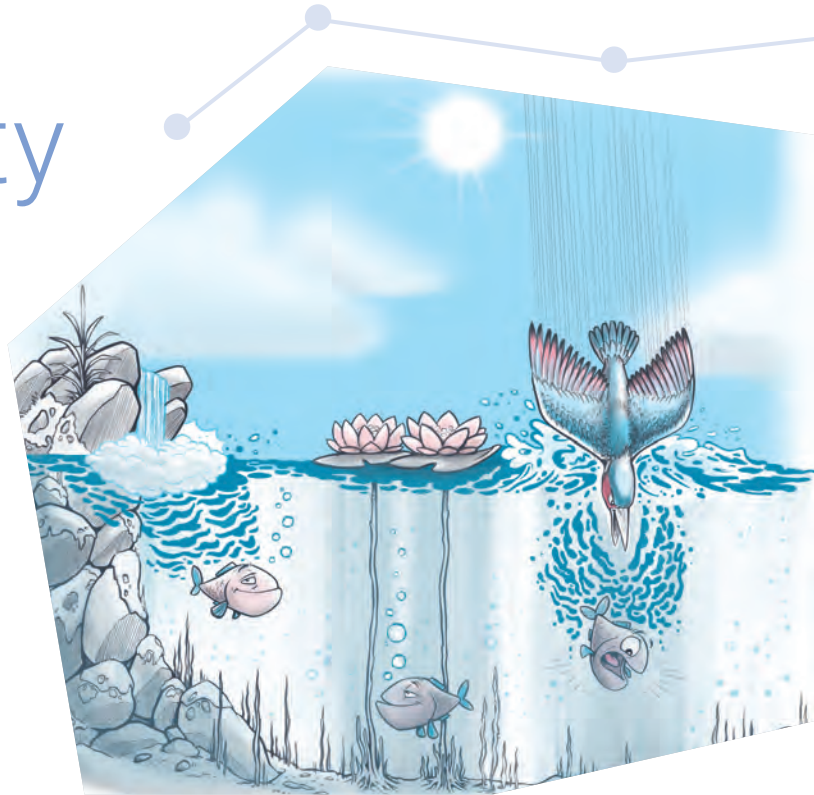


Definition

The candidate principle of **multimodality** maintains that processing information through multiple sensory channels is advantageous when operating in an uncertain and non-stationary world.

Multimodality

If you are reading this text, you are using multiple senses. Your vision allows you to recognize letters and follow lines of text, while touch helps you feel the pages, or your mouse, and control their movement. Even subtle proprioception – your sense of body position – helps you hold the book comfortably and keep your place. Using multiple senses at the same time helps intelligent systems understand the world more effectively, especially in situations that are uncertain, noisy, or constantly changing. Each sense provides overlapping but different information, so combining them gives a richer and more accurate picture than relying on a single sense. This simultaneous use of multiple sensory channels – for example, vision and touch – is called multimodality, and we believe that this is one of the principles of intelligence. In other words, relying on multiple channels when performing an action is a feature of intelligence.



Fish may respond only weakly to a shadow overhead or a disturbance at the water surface alone, but react strongly when both cues occur simultaneously, indicating a high likelihood of an attack by a fish-eating bird. So, intelligent systems can integrate information from different sensory modalities, such as visual and acoustic cues in our fish example, to generate more accurate assessments of their environment than would be possible when relying on a single sensory channel alone.

In biology, animals almost always rely on multiple senses to make decisions. For instance, fish can detect approaching bird predators more accurately by combining visual cues (such as the shadow of a bird passing overhead) with mechanical or acoustic cues (like vibrations or sounds in the water). A single cue alone may be misleading, but integrating multiple senses allows the fish to respond more quickly and effectively. This principle is widely observed across species: Animals constantly fuse sensory information to reduce uncertainty and improve survival.

We also see multimodality in synthetic agents. Imagine a robot closing a door. It can see that nothing is obstructing the doorway and hear the thump when the door closes. Using both senses together allows the robot to

act more safely and reliably than relying on vision or sound alone. This principle is especially important in robotics, autonomous vehicles, and other AI systems operating in complex, unpredictable environments.

Multimodality works because each sense contributes unique features about the same event. The brain, or an intelligent system, fuses these sense-specific features into a single, unified representation. This combined representation is synergistic: It can fill in gaps when one sense is noisy or incomplete, and it allows the system to weight more reliable senses more heavily. For example, seeing the position of a loudspeaker can change how we perceive the location of a sound, showing that different senses actively influence each other.

BY SOLVEIG STEINHARDT

Explaining the principle of *multimodality*

Lessons from Nature on Multimodal Intelligence

For humans, the usefulness of multisensory information is quite easy to grasp, because we simultaneously use different sensory channels all the time: when we eat (taste, smell, vision), or when we cross a busy street (vision, hearing). But is this a general pattern also found in other systems we consider intelligent, such as robots?

BY DAVID BIERBACH*



A snowy egret
attacking a shoal
of fish in Mexico.

According to the candidate principle of multimodality, the answer is “yes.” Indeed, most animals – from simple protozoans to our closest relatives, the great apes – rely on input from multiple sensory channels, and many sensory systems even come in multiples: humans have two eyes, spiders have up to eight, and dragonflies have thousands.

Maintaining numerous sensory systems is costly: You need neuronal tissue to process all the information at the same time – and sensors use up a lot of energy. And if it’s so costly, the benefits must be substantial. Identifying these benefits might be the key to why so many organisms use multiple sensors. It also shows us how that sensory information is processed in the most efficient way to generate the highest outcome from that heavy investment.

In natural systems, different sensory organs often provide very different types of information: for example, our eyes cannot see a smell, and our nose cannot smell a color. However, many sensory organs have slightly overlapping ranges (such as smell and taste, both detecting chemicals) or even largely overlapping detection ranges (such as our two eyes). Organisms possess a rich mixture of differently

overlapping senses, and this pool of information sources is precisely what constitutes the core benefit. We gain redundancy – so backup becomes possible. We gain diversity – so cross-validation becomes possible. We gain access to different distance ranges, and so on. All of this helps intelligent systems identify recurrent patterns in their environment, enabling them to respond in context-specific, optimal ways and ultimately make better decisions. Put simply, the more the sensors that can evaluate the same situation, the better that situation can be assessed, and the more robust the system becomes in its decision-making. And for organisms, this is life-saving, or “evolutionarily significant,” as biologists say.

At SCIOI, we investigate how animals use and integrate their multiple sensory systems, with the goal of applying these principles to artificial systems. For example, we study how small fish in Mexico avoid being preyed upon by birds (SCIOI Projects 12 and 41, also see p. 37). For these fish, it is a challenging task to determine when a bird is present, whether it is likely to attack, and where the attack may occur. A moving tree branch, a falling leaf, or the shadow of a vulture may resemble a kingfisher searching for a hunting spot. Correctly detecting whether a kingfisher is present and predicting where it will strike can save the fish’s lives. They may avoid certain areas or initiate anti-predator behavior by collectively diving, like falling dominoes, generating surface ripples that distract the bird – somewhat reminiscent of the so-called “olas,” or “Mexican waves,” in our football stadiums.

When kingfishers attack – often multiple times within a given area – they produce several sensory cues. As they fly over the water toward their target, they cast a moving shadow. Upon impact, they hit the surface with their full body, creating both a splash and a characteristic sound. Together, these cues serve as unique and unambiguous indicators of an attack and the presence of the predator. Our studies show that fish use all their senses to detect these signals and the strongest responses are observed only when visual and



A kingfisher with its freshly caught prey.

mechano-acoustic cues are perceived. This shows how these fish rely on multimodal sensory processing – integrating information from their eyes, lateral line system, and ears – to detect predator presence and attack locations.

More generally, using multiple senses allows organisms to acquire more information about a given situation, leading to better decisions. Consequently, the costs associated with maintaining numerous sensory systems are generally outweighed by the informational benefits. But this is not always the case. Not all senses provide relevant information, and those that don’t may disappear through degenerative evolution, in which the DNA encoding that sensory system accumulates mutations that impair its function, and without selective pressure maintaining the sense (higher survival rates and more offspring of individuals with working senses) it gradually degrades and may ultimately vanish, just like a species of cave-living fish we study at SCIOI, which are on the evolutionary path to losing their eyes. Simultaneously, the energy saved is invested in other, now more useful senses, such as enhanced lateral line systems that help the fish to sense their cave environment.

We believe multimodal sensory input is highly beneficial across intelligent entities and therefore constitutes a candidate principle of intelligence. It provides redundancy when one sensor fails, and offers richer information about the environment, enabling more robust decision making. ●

* David Bierbach is a post-doctoral researcher working on fish biology and behavior.

Multi-Timescale Computation

Intelligence is not only about adapting to changes in the environment – it is also about adapting to how quickly those changes happen. Humans, animals, and even artificial systems must constantly balance fast reactions with slower learning processes.

Human vision offers a clear example. Our eyes move rapidly, allowing the brain to scan a scene almost instantly and capture important details. At the same time, the brain remembers what it has already seen, preventing us from repeatedly focusing on the same objects. By combining quick snapshots with longer-term memory, the visual system efficiently tracks what matters, while ignoring what stays the same.

To understand why this is important, consider a standard security camera. It records images at a fixed rate, treating every moment as equally important, whether something meaningful happens or not. Only later can a human or an algorithm interpret the footage and identify relevant events. By contrast, the human visual system continuously adjusts its attention, prioritizing important changes while ignoring uninformative moments. New technologies such as event cameras (studied in SCIOI Project 36) move closer to this biological strategy by recording only meaningful changes instead of every frame.

Operating across multiple scales is an important part of intelligent behavior. A fast timescale allows a system to detect sudden changes, while a slower one integrates information over time, filtering out random noise and revealing stable patterns. The slower

process must strike a balance: slow enough to ignore fleeting fluctuations, but fast enough to keep up with real changes in the environment.

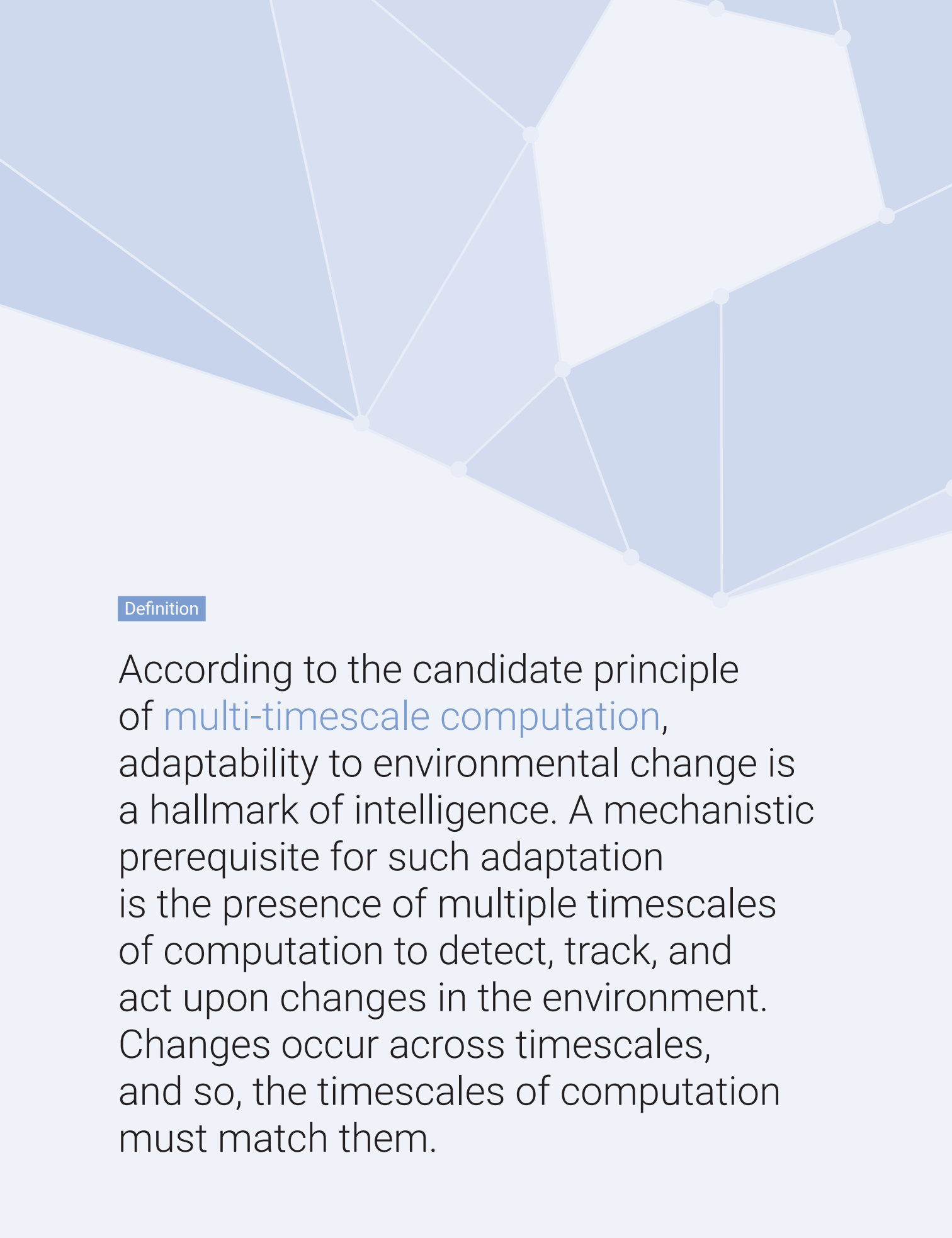
This principle appears throughout biology. Neurons fire in milliseconds, while learning occurs more slowly through changes in connections between neurons. The brain itself processes information across many layers of timescales, from rapid perception to gradual behavioral adaptation. Artificial intelligence faces the same challenge: Systems that learn in changing environments must balance quick responses with slower updating of knowledge.

This suggests that intelligence is not just about processing information – it is about knowing when to react quickly and when to learn slowly. *BY SOLVEIG STEINHARDT AND MARTIN ROLFS**



A sequence of brief visual impressions can be integrated over time, allowing us to perceive a running horse rather than a series of separate images.

* Martin Rolfs is a SCIOI Principal Investigator working in the field of vision science.



Definition

According to the candidate principle of [multi-timescale computation](#), adaptability to environmental change is a hallmark of intelligence. A mechanistic prerequisite for such adaptation is the presence of multiple timescales of computation to detect, track, and act upon changes in the environment. Changes occur across timescales, and so, the timescales of computation must match them.

Explaining the principle of
multi-timescale computation

Seeing with Purpose

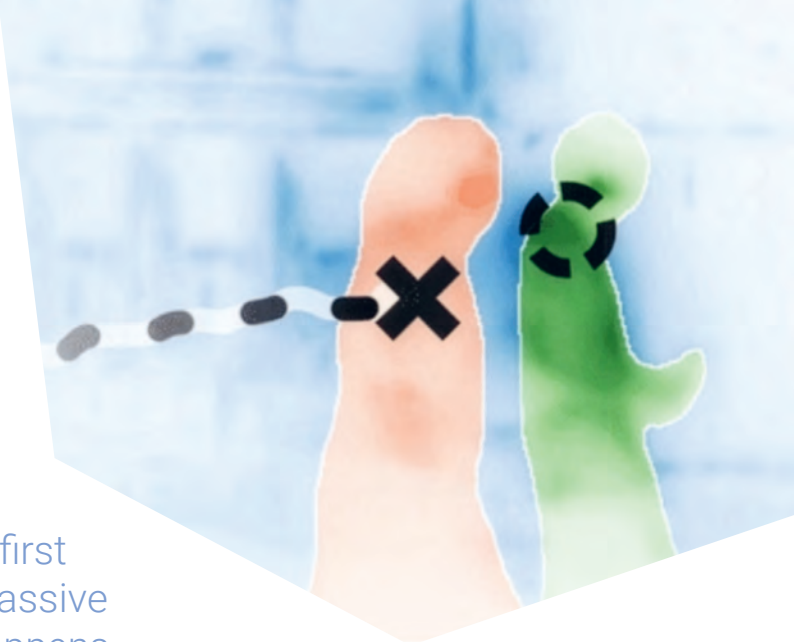
To act intelligently in the world, you first have to perceive it. Vision is not a passive process, recording whatever light happens to fall on the retina. It is an active, effortful process of inquiry: a continuous series of decisions about where to look, when to look, and how long to linger.

BY NICOLAS ROTH*

* Nicolas Roth obtained his PhD in computational neuroscience working on computational models of attention.

The world, meanwhile, certainly does not cooperate by staying still. Scenes change gradually and suddenly, predictably and without warning. Evolution has been ruthless in rewarding organisms that detect such changes quickly and respond appropriately. Nearly all animals with well-developed vision share a characteristic pattern of gaze behavior: periods of relative stillness called fixations, during which the eyes are roughly stable and the visual system integrates incoming information, punctuated by rapid jumps called saccades that redirect the gaze from one region to another. In humans, we trace this alternating rhythm through a tool known as “scanpath”, a spatiotemporal record of where the eyes went and how long they stayed.

The decision of where our eyes should go next must weigh fast, event-like signals of change against slower, accumulated understanding of the scene. This interplay, matching internal



Which object will
you look at first?

processing and exploration behavior to the rates of changes in the environment, can be seen as a direct manifestation of the candidate principle of multi-timescale computation. Our project (SCIOI Project 1) set out to understand this by building a computational model of gaze guidance in dynamic, naturalistic scenes.

Objects as the slow anchor

One of the oldest debates in attention research concerns what attention actually operates on: locations in space, or objects as coherent units? This question has real computational stakes. Pixel-level information changes constantly as lighting shifts, objects move, and people walk through a scene. Objects, by contrast, are the slow-scale structure of the visual world. A coffee cup, a pedestrian, a car door, maintain their identity across frames and fixations.

Through the development of a simulation model we called ScanDy (Scanpath simulation model for Dynamic scenes), we found evidence

that object-based representations provide a better account of human gaze behavior in dynamic real-world scenes than pixel-based alternatives. Our findings suggest that the gaze-guidance system anchors itself to the more stable, object-level structure of the scene. Related work within SCIoI reached a parallel conclusion in robotics: Processing objects one at a time allowed a robot to extract reliable depth cues that would otherwise prove difficult to recover. Attending to objects appears to be a computationally principled strategy that is not unique to biological systems.

Viewed through the lens of the principle of multi-timescale computation, fixations on objects represent the slow timescale: windows of integration during which the brain accumulates evidence and builds a stable foundation for subsequent action. Switching between objects, driven by saccades, is the fast timescale.

Saccades: active information requests

This raises an immediate question: How does the visual system know what an object is before it has looked at it? Our fovea, the small high-acuity region of the retina, covers only a few degrees of visual angle, and everything in the periphery is coarser and more ambiguous. Yet gaze is clearly not random.

Our model proposes that scenes are initially represented as uncertain, approximate object sketches – rough beliefs about what is present and where – that are gradually refined through successive fixations. Saccades are directed toward regions where the current representation is most uncertain and where looking is expected to yield the greatest information gain. Each eye movement is less of a reflex than it is an active question posed to the environment.

The information gathered during saccades also turns out to be richer than previously assumed. Contrary to the traditional view that vision is suppressed during eye movements, work at SCIoI suggests that even the brief, high-speed interval of a saccade carries useful

signals that contribute to perceptual stability and can help correct gaze mid-flight. The fast timescale, it seems, is not a gap in perception but a compressed episode of it.

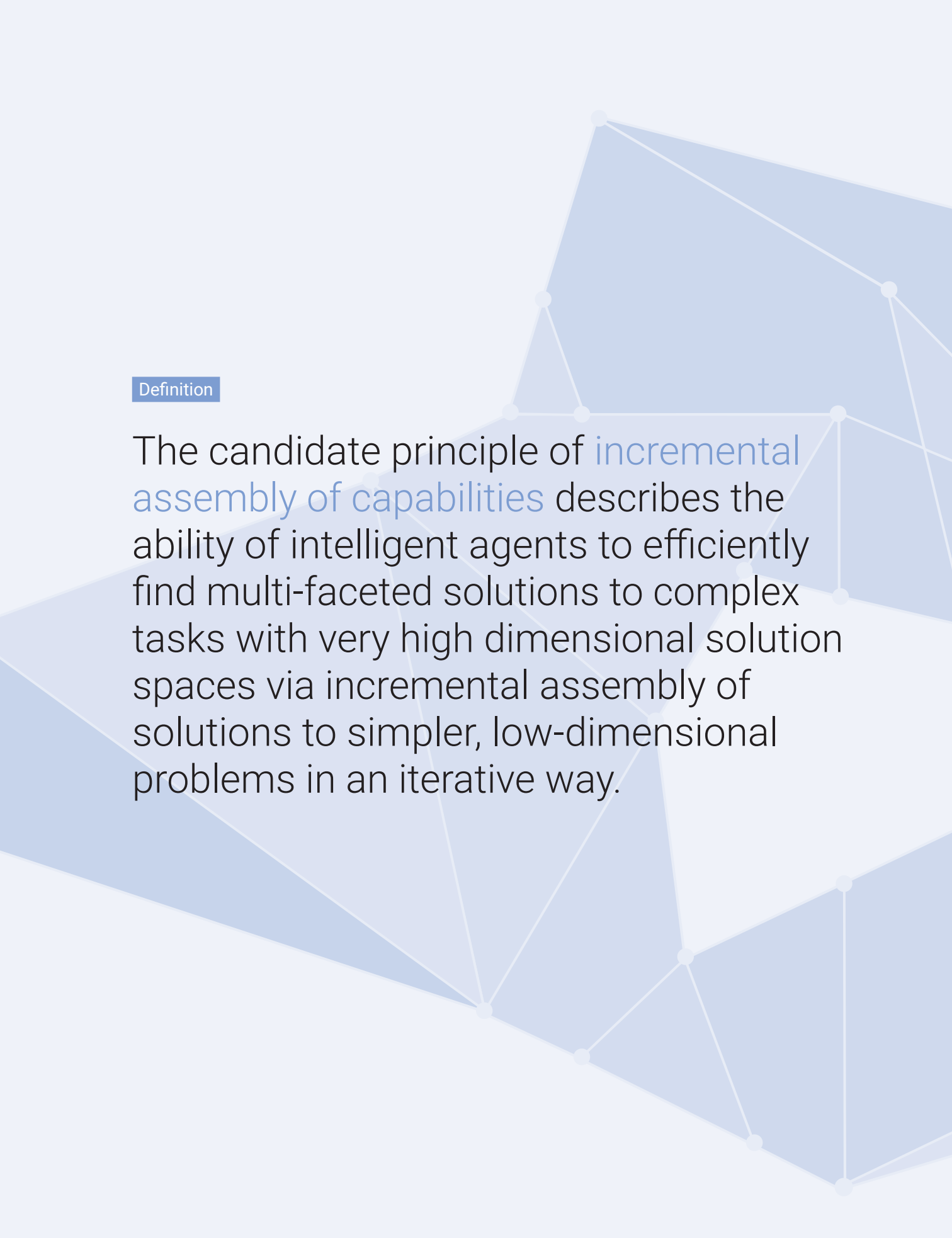
Adapting the clock to the environment

Perhaps the most striking property of this system is that it does not merely operate across timescales; it adapts them. We found that even when viewing visually identical static scenes, observers directed their gaze differently depending on whether they expected the scene to become dynamic. During the initial static phase, participants who anticipated change looked toward regions with higher potential for motion and activity, before any such change had occurred. This anticipatory shift was not limited to biologically salient stimuli like faces or animals; it appeared broadly whenever change could be expected.

Returning to our candidate principle, this is a direct example of an intelligent system dynamically tuning its internal sampling rate to match the expected temporal structure of its environment. The same sensorimotor machinery supports radically different gaze regimes depending on what the world is anticipated to demand. ●

An experimental setup used by SCIoI researchers to study how we see and what captures our attention.





Definition

The candidate principle of **incremental assembly of capabilities** describes the ability of intelligent agents to efficiently find multi-faceted solutions to complex tasks with very high dimensional solution spaces via incremental assembly of solutions to simpler, low-dimensional problems in an iterative way.

Incremental Assembly of Capabilities

A good way to tackle complex problems in high-dimensional spaces is to start with simpler problems in lower-dimensional spaces. By discovering simple regularities, an agent can replace some dimensions with prior knowledge, making the remaining problem easier to solve. Each new regularity the agent learns further reduces complexity, and these factors can be combined or recombined to generate more sophisticated behavior.

A clear example is how children learn mathematics: they start with addition, then build on

it to learn multiplication, and later division. Similarly, children develop motor skills gradually: they first control large, proximal movements before mastering fine, distal movements. This step-by-step process allows them to handle increasingly complex tasks.

In machine learning, a similar principle is used in curriculum learning. The system starts with a simple task, such as reaching for an object, and later moves to more complex tasks that rely on the earlier skills, like picking up the object. In both biological and artificial systems, mastering simpler components first helps make higher-dimensional, complex problems manageable. *BY VITO MENGERS*

When children play with building blocks, simple structures are assembled first, then combined step by step into increasingly complex ones.



Explaining the principle of
incremental assembly of capabilities

Learning, Step by Step

Imagine a mechanical puzzle consisting of a wooden board with several interlocking moving parts, where moving one element may lock or unlock another. Solving this puzzle, which is called a lockbox, requires not only discovering how each element moves, but also figuring out the correct order of actions. It is a task that even humans can find genuinely tricky when the mechanism is hidden. This is where the idea of an incremental assembly of capabilities first became concrete.

BY OUSSAMA ZENKRI*

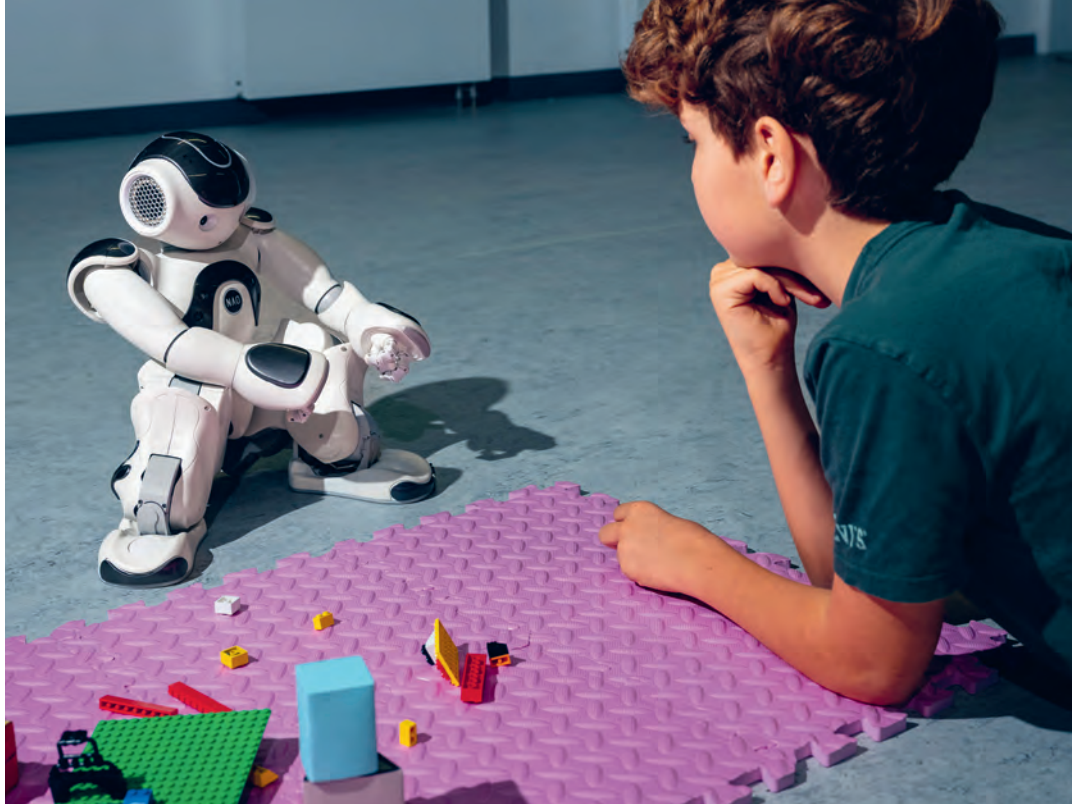


Robot solving a complex task, one step at a time.

In 2024, together with fellow researchers Xing Li and Adrian Pfisterer, I started working on a project (SCIoI Project 22) that would enable us to build a robot capable of handling tasks of this complexity, with the aim of making it robust enough to solve different variations of the problem without having to manually adapt the system for each one. The answer was not to build one highly specialized solver. Instead, we started from simple skills and incrementally assembled them into increasingly capable behaviors.

Our system begins with three basic components: perception, action, and planning. Perception detects the elements of the lockbox and estimates their locations. Action controls the robotic arm. Planning reasons about previous actions and their outcomes to decide what to attempt next. Each component handles a narrow, well-defined job. Individually, none of them can solve the lockbox. These basic skills constitute the first layer of capabilities.

The next layer of capability emerges when these components are assembled together. For



Children learn gradually, building on previous knowledge.

example, the robot has no prior knowledge of how a given joint moves. Rather than guessing, it performs a small exploratory movement, observes the result, estimates the joint's direction of motion, and then moves accordingly to gather more information. Perception guides action, and action produces better perceptual evidence. The behavior is not contained in either component alone; it arises from their assembly.

The same principle appears in how the robot positions its camera. To estimate the grasp location of a moving element accurately, it needs a good viewpoint: close enough to reduce noise in the depth sensor and centered enough to avoid distortion. The robot therefore moves actively to improve what it can see. Again, this behavior is not a feature of either capability on its own. It is what their assembly produces.

These newly assembled capabilities then become the raw material for the next layer. Once the robot has manipulated a joint, it can infer information about it, such as the type of kinematic joint it is dealing with. Planning can then use this information to make a more

informed guess about which joint is worth trying next. This behavior could not exist at the beginning. It depends on perceptual and motor capabilities that had to be assembled first.

This layered structure, namely simple capabilities, assembly of capabilities, and then new assemblies built on top of those assemblies, is what gave the system its robustness. When tested under conditions it had not been explicitly designed for, including different lockbox sizes, different arrangements of elements, shifted robot poses, and even broken fingers on the robot hand, the system kept working. Not because any single component was sophisticated enough to anticipate all these cases, but because the incrementally assembled capabilities were flexible enough to adapt to them.

The intelligent behavior we observed was therefore not engineered directly into a single module. It emerged from the incremental assembly of simple capabilities. ●

"We started from simple skills and incrementally assembled them into increasingly capable behaviors."

* Oussama Zenkri is a roboticist and a doctoral researcher at SClol.

Definition

The candidate principle of **adaptation of structure** states that in order to respond to long-term changes in its ecological niche or short-term environmental changes, an intelligent system may adapt its components to efficiently deal with such changes. These adaptations include removal or addition of components, but also the refactoring of existing components.



Adaptation of Structure

Intelligent systems, from animal brains to swarms of fish, can adapt not only their behavior but also their structure to meet new demands. This ability allows them to cope with environments that change in more fundamental ways.

In animal brains, structural adaptation often occurs over long timescales through evolution, gradually giving rise to new functions across generations. Swarm systems, however, can reorganize much more quickly. Unlike neurons in a brain, individuals in a swarm are mobile and constantly change their physical positions in space and time. As a result, the inter-individual connections are not fixed and are not reinforced as much between particular nodes but more conditioned by their movements and the immediate neighbourhood at a certain time. When faced with environmental pressures such as the presence of a predator, these spatial interaction patterns can rapidly reorganize, enabling the group to respond collectively in real time.

Structural adaptation also appears in artificial systems. Evolutionary algorithms allow synthetic agents to modify their organization to solve new tasks. Cognitive neuroscience describes a related process known as neural recycling, in which existing brain circuits are repurposed for new functions. Reading, for example, relies on visual brain regions originally evolved for object recognition, showing how cultural developments can reshape cognitive abilities. Similarly, adaptive robots can alter their configuration to operate effectively in different environments. In all these cases, structural adaptation allows systems to extend their capabilities beyond those directly specified by their initial design. (By contrast, this

does not hold true for non-intelligent systems, such as calculators, which are unable to reorganize their structure, despite their computational power).

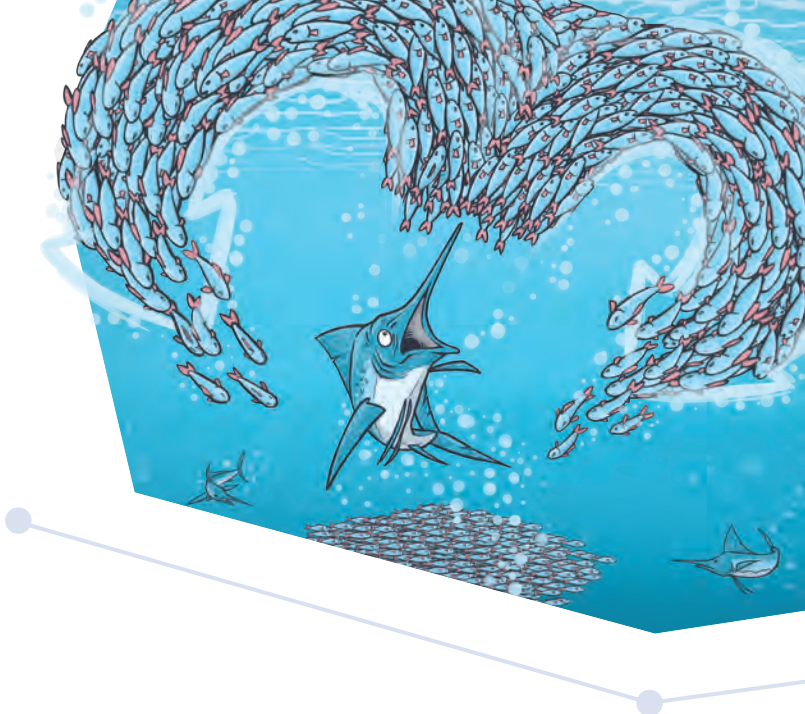
Structural adaptation differs from simply coordinating existing components. While flexible interconnections recombine available elements, structural adaptation redistributes capabilities to handle larger or longer-lasting environmental changes. These processes operate across multiple timescales, from adjustments within a lifetime to cultural and evolutionary transformations.

By reshaping their internal organization, intelligent systems can capture new regularities in their environment and expand what they are capable of doing. This flexibility is a central feature of intelligence in changing environments. An analogy from linear algebra is useful: Active interconnections combine existing basis vectors, whereas structural adaptation changes the basis vectors themselves. Taken together, this suggests that intelligence is not merely the optimization of behavior within a fixed structure, but the capacity to reorganize the structure that constrains and enables behavior in response to environmental demands, thereby expanding the space of possible actions across multiple timescales. *BY PALINA BARTASHEVICH**

When a predator approaches a fish swarm, the fish rapidly reorganize their formation, changing the structure of the collective to respond to the threat.

“Animal swarms can reorganize their structure to meet new demands.”

* Palina Bartashevich is a doctoral researcher at SClol working on collective behavior in biological and artificial systems.



Explaining the principle of *adaptation of structure*

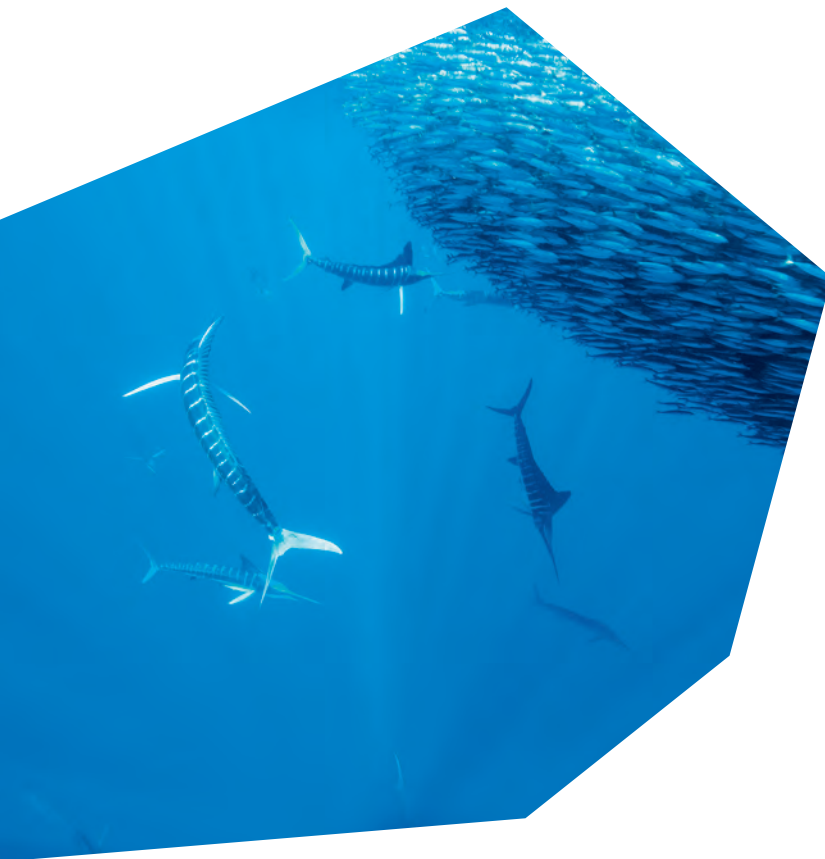
The Liquid Brain

The ability of a neuronal system to adapt its structure to the environment is one of the defining hallmarks of intelligence. While in the brain this happens over long periods of time (think of the evolution from the reptile brain to the mammal one), in more distributed neuronal systems such as swarms of bees, or flocks of birds, which some scientists sometimes refer to as “liquid brains,” this structural reorganization occurs rapidly before our eyes.

BY PAWEŁ ROMANCZUK*

A hallmark of biological intelligence is the ability to adapt and thrive in highly variable or changing environments. To a certain degree, this flexibility can be achieved through dynamical changes in behavior, while the system’s overall structure remains fixed. However, a defining feature of biological systems is their ability to tune and evolve their actual structure in response to new challenges and environmental changes. This stands in contrast to classical engineered computational circuits, which operate on fixed silicon architectures. The ability to adapt one’s structure to the environment is at the basis of the candidate principle of adaptation of structure.

Let’s take a classic example of how the brain adapts its learning: Over time, the connections between brain cells (synapses) become stronger or weaker, allowing us to store new information and skills. A similar principle is fundamental to artificial intelligence, where large amounts of data are used to adjust the weights of artificial neural networks during training. In neuronal systems such as the brain, structural adaptation typically occurs on timescales much longer than the behavioral dynamics themselves, and can only be evident



A marlin attacking a school of sardines.



Thymio, a small robot that acts in a group and communicates with others via visual impulses.

from an evolutionary perspective (think of the mammalian brain, and how its structure has evolved from, say, the reptilian brain).

This situation can be markedly different in other distributed biological systems that exhibit collective intelligence, such as fish schools or flocks of birds or swarms of robotic agents. Here, dramatic structural changes can occur rapidly and are often an integral component of the behavior itself. As a consequence, it can be difficult – or even impossible – to define a persistent structure of the collective across different tasks. This observation has led researchers to describe a collective that solves a problem by adapting its structure as a “liquid brain,” a term coined by Ricard Solé to describe a collective behaving like a neuronal structure.

At SCIOI we have studied several examples of collective behavior, and were able to observe instances where rapid adaptation of structure plays a decisive role in enabling collective intelligence. Fish, for instance, respond collectively to risk by quickly moving together and forming dense schools. The golden shiner, a small freshwater fish, releases a pheromone into the water – the so-called *schreckstoff* – when injured. This acts as an alarm signal indicating an increased risk of predation. When this “fright-causing substance” is introduced into the water, the fish get closer to their conspecifics and reorganize their group structure into compact and dense schools, all within seconds, then exhibiting more frequent and larger spontaneous collective escape responses. This brings us to a key question: To what extent does this change result from individual responsiveness and how much of it is due to structural reorganization, which enhances information transfer? By combining experiment and theory, we showed that the observed

change in collective behavior can be explained entirely by the structural adaptation of the group. In other words, the level of risk becomes encoded in the adaptive group structure itself. The giant escape cascades of sulphur mollies in response to bird predation (see p. 82), involving hundreds of thousands of individuals, represent one of the largest vertebrate systems exhibiting collective behavior, and their collective wave patterns are primarily controlled by the density of individuals, which the fish actively modulate.

Another example in which structural adaptation is essential for collective intelligence is collective foraging. Within SCIOI’s synthetic approach, researchers have investigated how a swarm of Kilobots – small mobile robots with minimal computational capabilities – collectively estimate the value of spatially distributed resources (SCIOI Project 27). Based on this, the swarm self-organizes and adapts its spatial structure to arrange around the maxima of the resource field.

When it comes to the concept of “liquid brain,” SCIOI research provides us with a great example involving a collective hunting experiment. Here, we observed the interaction of two antagonistic collectives: a group of marlin (the hunters) and a school of sardines (the prey) (Project 33). The dynamic structure and coordinated, fountain-shaped movements formed by sardines responding in unison can confuse predators. In particular, the sardines form a fountain-like coordinated movement around the predator, an optimal response when facing a faster but less maneuverable opponent.

Over the past years, we have made progress in understanding how structural adaptation constitutes a fundamental principle underlying (collective) intelligence. However, many important questions remain open – particularly concerning the mechanisms that allow these systems to adjust their structure in functionally beneficial ways despite being fully distributed, with each individual having only limited information and interacting with only a small number of nearby neighbors. ●

* Paweł Romanczuk is a Principal Investigator at SCIOI. He works at the interface of applied mathematics, theoretical physics, and behavioral biology.

Definition

According to the principle of **separating information into general and instance-specific**, in order to effectively learn from experience and robustly generalize learned actions, it is necessary to separate what is generally true from what is specific to a single situation. When an agent can separate these two types of information effectively, it becomes easier to learn from experience and apply knowledge to new cases, regardless of the details of the learning and acting process.

Explaining the principle of *separating information into general and instance-specific*

Teaching Robots to Generalize

When we set out to teach robots complex manipulation tasks, the goal is usually practical: Could a robot learn something like opening a drawer or inserting a key after watching just a single human demonstration, rather than hundreds?

BY XING LI*

At first glance, this seems straightforward. Humans do it all the time. But for robots, these tasks are notoriously difficult. They involve not just moving through space, but making contact – pushing, pulling, aligning, adjusting. And small variations matter. A drawer might be slightly misaligned. A lock might resist more than expected. Even tiny differences can cause failure.

Most scientists in the field have answered by giving robots more data, something known as “scaling up the amount of data.” When it comes to tasks related to language and vision, the strategy worked: trained on massive multi-task datasets, models generalize broadly. Many expect the same recipe to eventually work in

robotics. However, the current pipelines often fail to learn at the wrong level of abstraction for robotics, and so generalization across different or unseen task settings remains out of reach.

In our experiments (SCIoI Project 28), we took a different approach. Instead of asking the robot to copy movements, we asked: what is the structure of the task? We observed that many everyday manipulation tasks share common patterns. A drawer doesn’t move arbitrarily – it slides along a straight path. A door rotates around a hinge. These are not details of a specific object; they are constraints imposed by the environment. We call them environmental constraints.



Xing Li prepares his experimental setup.

From a single demonstration, our system extracts these constraints and represents the task as a set of behaviors that exploit them. Each behavior is anchored to a specific constraint and deliberately omits instance-specific quantities – object pose, orientation, and required force – leaving them as variables to be resolved online.

When the robot later performs the task, it fills in these missing pieces in real time. Using sensor feedback – especially touch and force – it adapts to the specific situation. If a drawer sticks, it pulls harder. If something is misaligned, it adjusts. Instead of rigidly replaying a motion, it follows the logic of the task.

The experiment gave very interesting results: With just a single demonstration, the robot successfully handled a wide range of tasks, including opening drawers, manipulating latches, inserting objects into tight spaces. And even when objects varied in shape or position, the system remained robust. It became clear that successful learning depended on separating two kinds of information. On the one hand, there is general structure – how a task works

in principle. On the other, there are instance-specific details – the exact conditions of a particular situation.

When these two are entangled, learning becomes brittle, and generalization fails. But when they are cleanly separated, learning becomes efficient, and generalization comes almost automatically. This observation led us to propose a new candidate principle of intelligence, which states that intelligent systems must separate general knowledge from instance-specific information in a task-appropriate way. In other words, the general component is learned once and reused; the specific component is inferred during execution. Such a structural bias is unlikely to emerge from data alone. The general part should be learned once and reused, while the specific details should be inferred as you go. This idea suggests that intelligence is not just about learning more data, but about structuring what is learned in the right way. In our case, a robot managed to learn from a single example and still adapted to the messy variability of the real world. ●

* Xing Li obtained his PhD and works in the fields of robotics, machine learning, and learning from demonstrations.



Science of Intelligence Conceptual Foundations

Can there be a definition of intelligence, and how did SClol researchers come to discover the candidate principles of intelligence? In the following pages we will be presenting some of the conceptual foundations that have driven our science in the past seven years.



Unifying Research on Biological and Artificial Intelligence

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Intelligence manifests across biological organisms and artificial systems, yet research on these forms remains fragmented by species, substrates, and disciplines. We argue that unifying intelligence research requires a substrate-independent conceptual framework that captures shared mechanisms of behavior generation.

We propose principles of intelligence as such a framework: general, mechanistic patterns that recur across biological and artificial systems, organizational levels, and ecological contexts. These principles describe how interacting system components process information to generate robust, goal-directed behavior under uncertainty. By enabling comparative, mechanistic analysis across domains, intelligence principles support incremental knowledge accumulation, foster integration between biological and artificial intelligence research, and lay the foundation for a unified science of intelligence.

Intelligence Across Biological and Artificial Systems

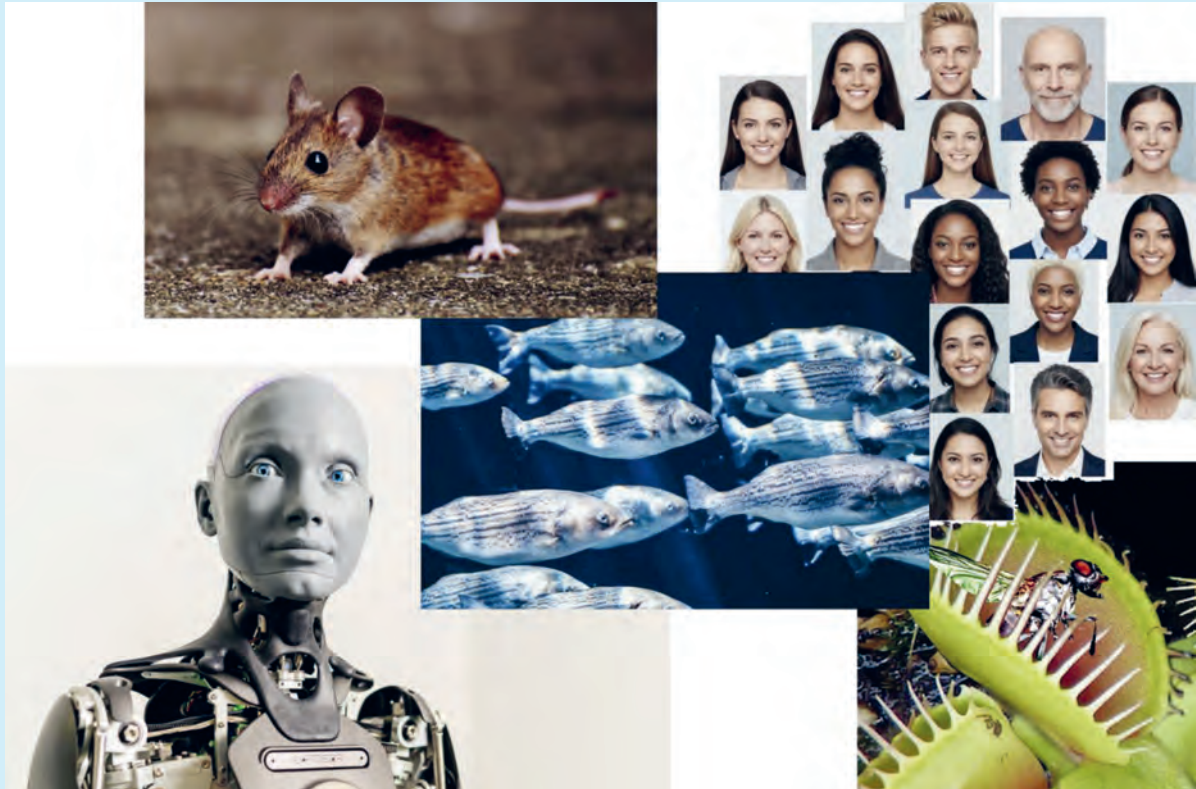
Intelligence (see Glossary, p. xiv) can be described as the ability to behave in a goal-directed manner in environments affected by ambiguity and uncertainty, while having access to incomplete information and limited resources. In addition to humans [1, 2], many species of animals exhibit behavior that complies with this description and provide examples of individual [3–6] or collective intelligence [7–9]. Recently,

there were claims of artificial systems (such as ChatGPT) showing some form of intelligence [10, 11]. Even the intelligence of plants is considered as a possibility by some [12, 13].

This diversification of instances of intelligence also challenges existing conceptual foundations of intelligence. Can we find a conceptual foundation that includes the disparate types of intelligences, across species and across substrates (i.e., specific physical implementation such as neurons or silicon)? An increasing number of scholars are calling for an approach to intelligence research that is not substrate specific [14, 15] and no longer centered on human intelligence and human brains as a reference point. Such an approach necessitates more abstract conceptualization [16–18]. These researchers argue that comparative cognition could be leveraged to gauge the cognitive capacities of AIs [16] and that AIs could benefit from insights into the cognitive abilities of biological systems [17], thus calling for a closer integration of biological and artificial intelligence [18]. However, it is still an open question how such a comparative approach can be implemented, given the diversity of manifestations of biological and artificial intelligences.

We see substantial promise in uniting research efforts and theoretical foundations across the biological and artificial realms. If the intuitive declaration of various examples as “intelligent” – across species, organizational levels (i.e., individual and collective) and substrates – is correct, then this would imply that all forms of

FIGURE 1: Different forms of intelligence. We propose that there are principles shared by all forms of intelligence, both biological and artificial. Identifying these principles can unify the diverse research agendas directed at understanding specific forms of intelligence.



intelligence share some underlying conceptual foundation (Figure 1). But to understand if this is true, we need an overarching conceptual framework that is independent of substrate, organisational level and species. Through such a framework, research in both realms might be able to overcome current foundational limits [19–28].

We propose unifying research on biological and artificial intelligence using principles of intelligence as the conceptual basis. These principles capture fundamental properties of intelligent systems that define how information is processed to generate intelligent behavior.

Principles of Intelligence

We suggest that principles of intelligence represent a novel approach to accumulate knowledge

about intelligent systems and compactly capture broad knowledge about many manifestations of intelligence.

Importantly, a principle captures systemic properties of behavior generation. This means that it does not pertain to a single functional component or a single type of behavior or species, but instead expresses knowledge of how several system components interact in the process of generating behavior.

Principles can be incomplete, which means that by themselves they may be insufficient to replicate the behavior in its entirety or to describe the intelligent agent in its entirety. However, being able to capture partial and incomplete knowledge becomes a precondition for a proactive scientific endeavor that incrementally accumulates knowledge.

Principles are general, in the sense that information processing patterns resemble each other, independent of the degree of abstraction of the processed information. Principles can therefore be identified by comparative analysis across the biological and artificial realms, across species, across behaviors, and across levels of abstraction.

Over the past years, we have identified a number of candidate principles. As part of an ongoing research program, these principles are inherently tentative and await further validation and elaboration. Below, we will outline three examples to illustrate the principles' concept. Based on these examples, we describe how new principles can be identified and how they can help shape intelligence research across the biological and artificial realms.

Example 1: Principle of Agent-Environment Coupling

Intelligent agents produce robust behavior by exploiting regularities in the world. Regularities are reliably occurring relationships between aspects of the world. Newton's laws of motion are examples of such regularities. Other examples include gravity or motion parallax.

The principle of Agent-Environment Coupling states that an intelligent agent creates novel and task-relevant regularities by coupling itself to its environment. The regularities of the coupled agent/environment system are then exploited to generate intelligent behavior.

An instantiation of this principle is depth perception from fixation [29, 30]. The agent couples itself to its environment via visual perception. During its own motion, it keeps a feature of the environment in the center of its visual field (fixation). This fixation produces a new perceptual regularity. Objects between the agent and the

fixation point and objects behind the fixation point will now move in opposing directions as the agent moves and fixates. A depth perception problem has been simplified to detecting the direction of visual flow, reducing computational costs and increasing robustness.

Depth estimation based on fixation, as an instantiation of the principle of Agent-Environment Coupling, can be found in the human visual system [29] as well as in artificial robotic agents [30], bridging the biological and artificial realms. But there are many more instantiations of the principle. For example, whenever biological or artificial agents make contact with their environment to locomote or manipulate, this principle is being applied [31, 32].

Example 2: Principle of Multiple Computational Paradigms

Computation can be implemented in different paradigms, including the most familiar in biological agents such as neural computation and mechanical computation. In synthetic agents the most common paradigm is digital computation, but analog computation, quantum computation, and mechanical computation are also being actively researched [33]. Associated with each of these paradigms is a set of computational problems for which that paradigm is the most suitable one. For example, quantum computation is likely the most effective way to factorize large integers while differential equations can be solved effectively using analog computation.

The principle of Multiple Computational Paradigms states that the robustness and versatility of intelligent behavior results – at least in part – from the synergistic application of multiple computational paradigms.

A compelling instantiation of this principle can be found in human and robotic grasping. Both humans and robots effectively outsource the computation of specific contact locations and forces during routine grasping to the mechanical computation implemented in the mechanical properties of the hand [34–36]. By solving the problem of computing contact location and forces using mechanical computation, humans and robots avoid the necessity for physically accurate models of hand and environment, reduce the amount of digital/neural computation required, and at the same time increase the robustness and versatility of manipulation behavior.

This principle plays an important role whenever an agent interacts with its physical surroundings. This might be particularly evident in biological species where the morphology was adapted to the specific characteristics of the ecological niche via evolutionary processes.

Example 3: Principle of Active Interconnections

Intelligent agents, no matter whether biological or artificial, consist of identifiable components that interact with each other to produce intelligent behavior. Intelligent behavior arises from the behavior of the components but – to a large degree – also from the interactions among the components. Such a system exhibits a low degree of modularity and is called weakly decomposable, which presumably holds true for most if not all intelligent systems. To study weakly decomposable systems, it is essential to study and characterize the interactions among components at various levels of abstraction [37].

The principle of Active Interconnections states that the components of an intelligent system must communicate with each other via active interconnections. An interconnection is

active if it shapes the information being passed in accordance with the state of the overall system. This shaping is equivalent to a mathematical constraint imposed on the way the connected components can change their state. These constraints are derived from regularities present in the world.

In its most generic form, this principle is instantiated ubiquitously in many different contexts, ranging from interconnections between brain areas, the information exchange among individuals in a flock of birds, or the data passed among components in a robotic system [46]. But, more specifically, active interconnections dynamically encode constraints that tie the behavior of the interconnected components together. Constraints encode current knowledge about the world and enforce that the system's state remains consistent with the constraints known about the world. This results in such a strong reduction of the state space that intelligent behavior becomes possible, even with limited computational abilities.

Instantiations of the principle of Active Interconnections can be found in the biological and artificial realms. Importantly, it has been developed into models to specify robust behavior of robots [38], to model the human visual system [39, 40], and to reproduce the behavior of agent collectives [41]. The effectiveness of this principle can be illustrated in the context of robotic systems. One of the great challenges in building complex robotic systems consists in ensuring that all “special cases” are handled so that the robot can act sensibly, even when the environment varies. A model based on active interconnections [38] seems to side-step this challenge entirely. A simple behavioral model is able to generate suitable behavior for a wide range of unanticipated situations, even though these situations were

never conceived of at the time of building the system [38].

Deriving New Principles of Intelligence

To help identify new candidate principles, we analyze the properties principles of intelligence must have. Maybe the simplest way to think about principles is as follows: Scientific studies pertaining to intelligence produce models of agents that behave intelligently. As outlined above, principles are design rules for constructing such models of intelligent agents. Thus, identifying principles will help to generate models of intelligent agents.

To understand principles better, we distinguish between descriptive and mechanistic models. A descriptive model captures the statistics of measurable properties of behavior. A mechanistic model is a descriptive model which also captures the process that brings about the behavior.

We advocate that principles of intelligence must be mechanistic, i.e., they must capture the process that brings about the behavior. The process of behavior generation must be based on compositionality. Therefore, to understand intelligence, we must identify the mechanistic components that, when interconnected adaptively, generate intelligent behavior. The principles are mechanistic “templates” for the construction of concrete components instantiated in biological and artificial agents.

Principles of intelligence capture mechanistic patterns that recur in different species across biological and artificial substrates, in different ecological niches, and on many levels of abstraction. They represent a mechanistic pattern that has proven to be useful in intelligent agents. We have identified a number of such patterns, listed as candidate principles in [Box 1](#).

Given that principles capture mechanistic patterns and not fully instantiated systems, principles must be compositional. This allows several principles to be applied at the same time to constrain the space of possible mechanical realizations for a specific agent.

Bridging Analytic and Synthetic Approaches

We believe that principles of intelligence can serve as an effective tool to guide and accelerate intelligence research (most of the references in this paper attest to that) without disrupting the established practice.

Principles of intelligence have the potential to unify the analytic and synthetic realms of intelligence research. The mechanistic process of behavior generation can be specified in a substrate-agnostic manner [38]. The insights and empirical results captured by a principle therefore apply equally to both realms [38, 39]. Insights from one realm can immediately transfer to the other. This enables comparative research across realms, offering the potential of bringing together complementary insights and complementary research approaches towards a unified scientific objective.

Substantial synergies arise from the fact that biological systems exhibit truly intelligent behavior but are difficult to study, whereas artificial systems offer unlimited access to their internal state. This synergy could prove particularly helpful with modern large-language-model-based AI systems that have become too complex for a complete understanding in spite of this unlimited access [21, 23]. Applying analytic methods and principles to artificial systems could open the door for AI models whose results can be explained in terms of their mechanistic components.

Box 1

Candidates for Principles of Intelligence

Active interconnections: The principle of active interconnections states that the components of an intelligent system (for example, the different areas in the brain) must communicate with each other via active interconnections. An interconnection between several components is active if it couples the behavior of the components so as to be consistent with a constraint the world imposes on them. This constraint is not reflected in the components themselves but in the active interconnection instead.

Multiple computational paradigms: The robustness and versatility of intelligent behavior result – at least in part – from the synergistic application of multiple computational paradigms (e.g., neural and mechanical computation).

Agent-environment coupling: The generation of intelligent behavior leverages a flexible coupling of the agent to the environment. Through this coupling, the agent can create novel, task-related regularities. These, in turn, are exploited during the generation of intelligent behavior.

Adaptive representations: Behavioral flexibility is facilitated by adjusting the representations of the world state to the agent's environment, task, and goal. Adaptive representations capture aspects of the world in a way that is most conducive to generating that behavior.

Multimodality: The principle of multimodality states that processing information through multiple sensory channels is advantageous when operating in an uncertain and non-stationary world.

Multi-timescale computation: Adaptability to environmental change – whether over time or across space – is a hallmark of intelligence. This adaptability requires the presence of multiple scales of computation including the ability to differentiate and integrate, to detect, track, and act upon changes in the environment.

Incremental assembly of capabilities: The principle describes the ability of intelligent agents to efficiently find multi-faceted solutions to complex tasks with very high-dimensional solution spaces, via incremental assembly of solutions to simpler, low-dimensional problems in an iterative way.

Adaptation of structure: The principle of the adaptation of structure states that an intelligent system, to respond to long-term changes in its ecological niche or short-term environmental changes, may adapt its components to efficiently deal with such changes. Such adaptations include removal or addition of components, but also the re-factoring of existing components.

Separating information into general and instance-specific: This principle states that effective learning from experience and the robust generalization of learned action policies requires the careful separation of general and instance-specific information. If this separation is performed in a task-appropriate manner, learning and generalization are a natural consequence, irrespective of the details of the learning and acting process.

Principles can contribute to the *formulation of hypotheses and models* and allow the effective elimination of models that would contradict a pertinent principle [39]. Principles can thus become an important driving force for analytic research (Box 2) because they can motivate research across different study systems to identify commonalities. Principles can also shape ideas for experimental work or provide mechanistic models for testing.

Principles of intelligence permit the *incremental accumulation of partial, mechanistic knowledge* about intelligence. We have already argued that an understanding of intelligence must be captured mechanistically. Since the internal structure of intelligent agents is highly complex, it is not plausible to articulate a complete mechanistic description of an intelligent agent without first understanding some aspects of the agent. Principles offer the possibility of understanding, capturing, and applying such understanding of partial aspects. Therefore, principles support a community-wide research program in which an increasingly complete understanding of intelligence is built in a distributed manner.

Principles of intelligence can act as an analytic tool to *group and categorize prior work*. Results from distant areas, different species, and different levels of abstraction can be placed in a shared context if they can be explained via joint principles [32, 36, 39]. This can help gather diverse support for principles, identify inconsistent results, and accelerate the generation of new experimental hypotheses. This strengthens the conceptual foundations for comparative research, even among very different species, across artificial and biological substrates, and at different levels of abstraction.

The principles of intelligence also advance research in artificial intelligence. In the context of building intelligent systems, the principles guide the design process, reduce computational requirements, improve data efficiency, and can help address challenges of explainability. We provide specific examples in Box 3.

The principles of intelligence unify the study of biological and artificial intelligence. By contributing to research in both analytic and synthetic disciplines, the principles provide an effective way to translate established knowledge across disciplinary boundaries, to formulate substrate-independent research programs, and to build an understanding of intelligence that covers animals, humans, and artificial entities. Principles of intelligence can fulfill this function as they address a key aspect of intelligence, namely, the challenge of addressing the complexities of the real world (see next section).

The discovery of new principles and the validation of existing ones is probably most easily achieved in *comparative research* across diverse axes of comparisons. Principles of intelligence are mechanistic patterns. And patterns can be most easily identified in situations when most aspects of the situation are different so that the pattern can stand out. It is therefore helpful to push the boundaries of comparative research across many disciplines, species, and substrates to advance the identification of principles of intelligence.

We believe that adopting principles of intelligence as a conceptual tool in intelligence research can help achieve substantial progress while fully leveraging the existing body of research.

The Challenge of Addressing Real-World Complexity

In his 1954 book *The Foundations of Statistics*, the mathematician Leonard J. Savage (1917–1971) described a comprehensive theory of statistics. He distinguished decision making in **large** (he calls them “grand”) **and small worlds** [42, 43]. This distinction can play a crucial role in understanding intelligence. We believe that the principles of intelligence enable agents to act intelligently in large worlds while relying on small-world models.

In a small world, the world’s state can be described exactly. We know with certainty how actions change the state. We can devise a model that captures all aspects of the small world. Interestingly, many of AI’s historical showcases are small-world problems: chess, the game Go, automated proofs, and language. Effectively, all models are small-world models.

In large worlds, an agent has limited access to the state of the world. The rules according to which the world changes are not fully known. No matter how sophisticated a model might be, it will never capture the dynamics of a large world. There is no accurate model of a large world other than the large world itself.

Intelligent agents inhabit large worlds. For such worlds, a well-known aphorism, often attributed to George Box, states that all “models are wrong, but some are useful.” To act intelligently in a large world, an agent must overcome the gap between its internal model (necessarily a small-world model) and the large world. The principles of intelligence ensure that the small internal models of the agent are useful for acting in the large world.

Leveraging principles in generating behavior ensures that the action chosen by the agent based on its small-world models is almost

always the same as the action selected based on complete knowledge of the world state [42]. Principles enable this translation because they capture fundamental regularities in the large world. These regularities map a noisy and uncertain world onto a **constraint manifold** imposed by this regularity. This projection reduces the dimensionality of the **state space** significantly and in a way consistent with the task-relevant structure of the large world, thereby enabling intelligent large-world behavior based on small-world models [38].

This principle-based translation can fail, of course, as the small-world model does not capture all aspects of the large world. Then we observe mistakes, e.g., visual illusions or cognitive biases. Principles capture highly relevant regularities but might ignore others. This is probably an inherent property of intelligence: it is not universal.

Towards a Science of Intelligence

If we follow the idea of unifying intelligence research to its very conclusion, the logical step is to move beyond interdisciplinarity, which by definition implies a research environment compartmentalized into disjunct disciplines – each with its own specific language, research tradition and core research questions – towards a new unified discipline, a science of intelligence. In a nutshell, we propose to take the original idea of cognitive sciences and develop it further to transfer it into the age of AI. This new discipline must share a unified scientific language and a methodological ecosystem that are substrate-independent, seamlessly apply across all intelligent species – whether biological and artificial – and thus naturally support comparative research on intelligence on a new, unprecedented scale. Only such a massively comparative

Box 2

How Principles Can Be Used in Analytic Research

The design of an experiment, the formation of a hypothesis, and the modeling of experimental data in an attempt to produce an explanation – all rely on some form of prior knowledge. The use of such knowledge is necessary to be able to select from the huge set of possible statements that are more likely to lead to an insight, to support a hypothesis, or yield data that is interpretable and produces new knowledge.

The Principles of Intelligence represent such prior knowledge in the form of inductive biases, which are a known prerequisite for learning generalizations [47]. Each principle is empirically supported across species, levels of abstraction, and organizational forms of intelligence. This implies that the inductive bias encoded in the principle is general and has broad empirical support and applicability.

Principles are a simple way of incorporating the knowledge produced by prior studies into one's research as an inductive bias. They are a compact way of representing general knowledge. This facilitates leveraging prior work and it facilitates conceptual consistency across studies.

How can principles be used?

1. Just knowing the principle can already influence one's thinking, eliminate some possibilities as unlikely, or suggest directions to explore that might be deemed unconventional otherwise. The principle can serve as a mnemonic. It is easy to remember, a simple heuristic, a compact representation of studies on knowledge one might otherwise not be aware of.
2. Principles can be used as mechanistic components of models or to structure models to be consistent with the principle. Making a model consistent with a principle should increase the model's generality and accuracy. This is because the inductive bias selects, from all models consistent with the data, those that are also consistent with other things we know about intelligent agents. This reduces the set of possible models we have to consider.
3. The principles provide patterns that can be matched onto a particular area of study. For example, the Principle of Active Interconnections suggests two types of entities: Estimators of world state and constraints between those estimators. The model building in research can now attempt to cast relevant model components into these two types of components. The structure encoded in the principle and associated model adds a useful inductive bias.
4. Principles can help to find commonalities among published studies. This helps structure existing knowledge and gathers more support for the principles themselves.

Box 3

How Principles Impact Research on Artificial Intelligence

The principles of intelligence can guide the synthesis of artificial intelligences. A valid principle, if implemented in an artificial agent, contributes to increased robustness and versatility of the agent's behavior. It also reduces the computational requirements and improves data efficiency in learning. We illustrate some applications of principles to different aspects of artificial agents.

Programming behavior: The principle of active interconnections represents a modeling language for intelligent agents [38]. To transfer the principle into the artificial realm, we created a domain-specific programming language based on active interconnections that produces increased robustness and versatility in behavior generation when compared to existing approaches for programming robots and embodied intelligent agents [38].

Co-design: The principle of multiple computational paradigms implies that the generation of intelligent behavior best be distributed across mechanical computation of the body [48] and explicit computation (digital or neural). This insight has given rise to the field of soft robotics [49] that propagates the co-design of hardware and software to produce intelligent agents. These ideas led to substantial progress, for example, in the domain of robotic manipulation [50, 36].

Data efficiency: Machine learning theory states that inductive biases improve generalization and increase data efficiency [47, 51]. The principles of intelligence provide excellent inductive biases. An approach to learning

from demonstration leveraging at least three of the principles described in [Box 1](#) solves benchmark problems from the deep learning community [44] with a single demonstration [45], where deep-learning-based approaches require hundreds of demonstrations to achieve only partial success.

Deep Learning: The success of deep learning relies on the ability to form intermediate representations distributed across the network [52]. It is plausible that these representations and their interactions approximate the principles of active interconnections and adaptive representations. Currently, these useful internal structures must be learned from large amounts of training data. Adjusting the network's architecture and the training procedure to favor the formation of substructure in the network that reflects the principles of intelligence could produce substantial improvements in learning performance and data efficiency.

Explainability and alignment: The interpretation of deep neural networks is challenging, due to the distributed nature of the implemented computation. For some intelligent agents, especially in ethically sensitive applications, it will be important to expose the factors that produced an answer (explainability) [53] and to influence this answer to be consistent with society's values and laws (alignment) [54]. Both challenges can be greatly facilitated if the internal structure of networks is biased towards the principles of intelligence.

approach will enable us to reliably quantify high-level mechanistic patterns shared across intelligent systems, and thus allow us to identify principles of intelligence. This collection of principles must be a dynamic process. Patterns of intelligent behavior identified in multiple species are initially treated as candidate principles, and have to become objects of investigation themselves. Some of the candidate principles we have identified are listed in [Box 1](#). Their presence in other species needs to be tested, their potentially diverse implementation into different intelligence substrates needs to be mapped and understood, eventually allowing us to strengthen the empirical support for this recurring pattern to be a principle of intelligence, or to invalidate the candidate principle. The success of such a unified science of intelligence, naturally bridging from neuroscience via cognitive science and ethology to computer science and robotics, will crucially depend on a parallel evolution of the academic environment supporting intelligence research across traditional disciplinary boundaries. This includes the proliferation of corresponding funding opportunities, novel conference formats for scientific exchange, and dedicated publication venues.

Concluding Remarks

The proposed conceptual approach based on intelligence principles is substrate-independent and therefore holds the potential for convergence of traditional disciplines of intelligence research, spanning across biological and artificial forms of intelligence. Research on biological forms of intelligence has a long-standing tradition whereas research on large language models (LLMs) and other such systems of artificial intelligence is relatively novel. Integrating both lines of inquiry based on a search for commonalities and differences is facilitated by substrate-independent

mechanistic principles at the heart of their performance. Such an integration towards a "science of intelligence" would be facilitated by a rigorous comparative methodology, systematically examining intelligence across natural and artificial systems.

A unified science of intelligence can potentially deliver a number of much-needed advances on the common state of the art using primarily machine-learning. Computation based on intelligence principles requires far less training data [44, 45] because existing regularities expressed in the intelligence principles are utilized, which reduces parameter space. This approach also means that much less energy is consumed [38, 45] and clear cause-and-effect relationships can be provided, creating transparent AI in line with ethical expectations [28, 36]. In some cases, intelligence principles have also been shown to lead to better solutions than machine learning [44, 45]. Finally, a unified intelligence discipline would provide a home for all current disciplines with a bearing on intelligence research thereby allowing for a much more diverse input repetition than we currently see today. Importantly, the approach using intelligence principles would provide a structured way in which these disciplines can express their insights in a "common currency."

Outstanding Questions

Are there principles that must be present in all intelligent agents, or can intelligence exist in partial or minimal forms?

How do principles of intelligence interact mechanistically – are some hierarchical, mutually dependent, or mutually exclusive?

Can principles characterize intelligence completely, or are additional concepts required?

Can non-neural biological systems (plants, fungi, collectives) reveal principles absent from animal cognition?

Which principles of intelligence are particularly prominently developed in biological and artificial systems, respectively?

What is the relationship between principles of intelligence and traditional cognitive functions such as memory, attention, or reasoning, as well as established methods in AI such as reinforcement learning?

Are all principles and their combinations synthesizable, i.e., can principles provide a “programming language” for artificial intelligent agents?

What new analytic tools are needed to reverse-engineer complexity in artificial systems like LLMs using a principle-based framework?

Can principles be combined systematically to generate artificial agents with novel forms of intelligence not found in biology?

How do principles of intelligence emerge over ontogeny and learning within biological organisms?

Do ecological niches drive the implementation of different sets of principles in different agents?

Glossary

Active interconnection: A proposed principle of intelligence where components of a system exchange information in ways that depend on – and constrain – the overall system state, enabling coordinated behavior in high-dimensional and uncertain state spaces.

Agent, intelligent agent: An entity (biological or artificial, individual or collective) that perceives, acts, and adapts under resource limitations within an environment characterized by uncertainty and incomplete information.

AI: Artificial intelligence or, in plural, agents based on artificial intelligence technology, predominantly deep learning and large language models.

Analytic and synthetic intelligence research: Analytic research studies biological intelligence using analytic methods. Synthetic research synthesizes technological artifacts to investigate intelligence by building it. The resulting synthetic agents can be analyzed with analytic methods to gain insights, also in comparison to biological agents.

Constraint (manifold): Low-dimensional structures or relations that restrict the system's possible states, making effective behavior possible in otherwise vast, high-dimensional state spaces.

Intelligence (biological and artificial): Intelligence is the ability to produce adaptive and goal-directed behavior in environments characterized by uncertainty, incomplete information; scientists do not yet agree upon a concise definition; the target of understanding of many disciplines.

Large Language Models (LLMs): AI systems based on deep neural networks trained on large text corpora that generate behavior through high-dimensional statistical modeling rather than traditional cognitive architectures.

Mechanistic and descriptive models: A *descriptive model* captures the statistics of measurable properties of a (behavioral) phenomenon. A mechanistic model is a descriptive model that also captures the process that brings about the phenomenon.

Principles of intelligence: Mechanistic, cross-domain regularities that govern how intelligent behavior is produced; these principles apply across species, substrates, and levels of abstraction.

Regularity: A regularity is a consistently recurring, predictable, and describable relationship between characteristics of a system. A regularity defines a lower-dimensional manifold embedded within the overall state space that can serve as a constraint in an interactive connection.

Small & large world: For small worlds, the state space can be described exactly, we can know the “necessary,” describe how actions change the world state. In large worlds, an agent only has limited access to a noisy and uncertain world state, the range of outcomes of the agent's actions is not fully known, and the regularities based on which the world changes its state are not fully known (following Leonard J. Savage).

State space: The state space describes all possible internal and environmental states an agent and its environment can be in; typically, it is extremely large, high-dimensional, and riddled by uncertainty in real-world conditions (see also small & large worlds).

Substrate: The physical implementation of information processing in an agent (e.g., silicon/transistors versus carbon-based/neural).

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DECLARATION OF INTERESTS:

No interests are declared.



Making it All Happen

A look inside the SClol
coordination office



At the SNDs 2026: a networking
event that brings scientists together.

What Is a Cluster of Excellence?

A Cluster of Excellence is a long-term (seven years or more) funding program within the German Excellence Strategy, jointly funded by the German Research Foundation (DFG) and the federal states. Its purpose is not only to support individual research projects, but also to strengthen universities by building internationally visible research environments and by structurally developing entire fields of research.

Clusters are awarded through a highly competitive, peer-reviewed selection process. Participating universities define a shared research agenda and establish coordinated structures that integrate expertise across institutions.

SCloll is a Cluster of Excellence based in Berlin and Potsdam, involving Technische Universität Berlin, Humboldt-Universität zu Berlin, Freie Universität Berlin, Charité – Universitätsmedizin Berlin, Universität Potsdam, and the Max Planck Institute for Human Development. Its mission is to explore the principles of intelligent behavior in order to understand intelligence.

In this sense, Clusters provide stable yet flexible frameworks for field development, enabling sustained collaboration, methodological innovation, a certain amount of management freedom, and long-term scientific impact beyond the conventional individual projects and funding cycles characterizing German research.

Boards and Structure

Our boards advise on the Cluster's main decisions in day-to-day matters, scientific affairs, and ethical issues.

The SCloll Executive Board

Elected by the Cluster members, the SCloll Executive Board is responsible for all major decisions within the Cluster and for developing the SCloll research program. The board also decides on policies and funding applications, determines the admission of collaborating PIs, advises on budgeting decisions, and oversees quality assurance within the Cluster.

The SCloll Committees

Eight committees assist the Executive Board on various matters, such as admissions, curriculum development, doctoral program, equal opportunities, ethical responsibilities, quality assurance, research data, and team advancement.

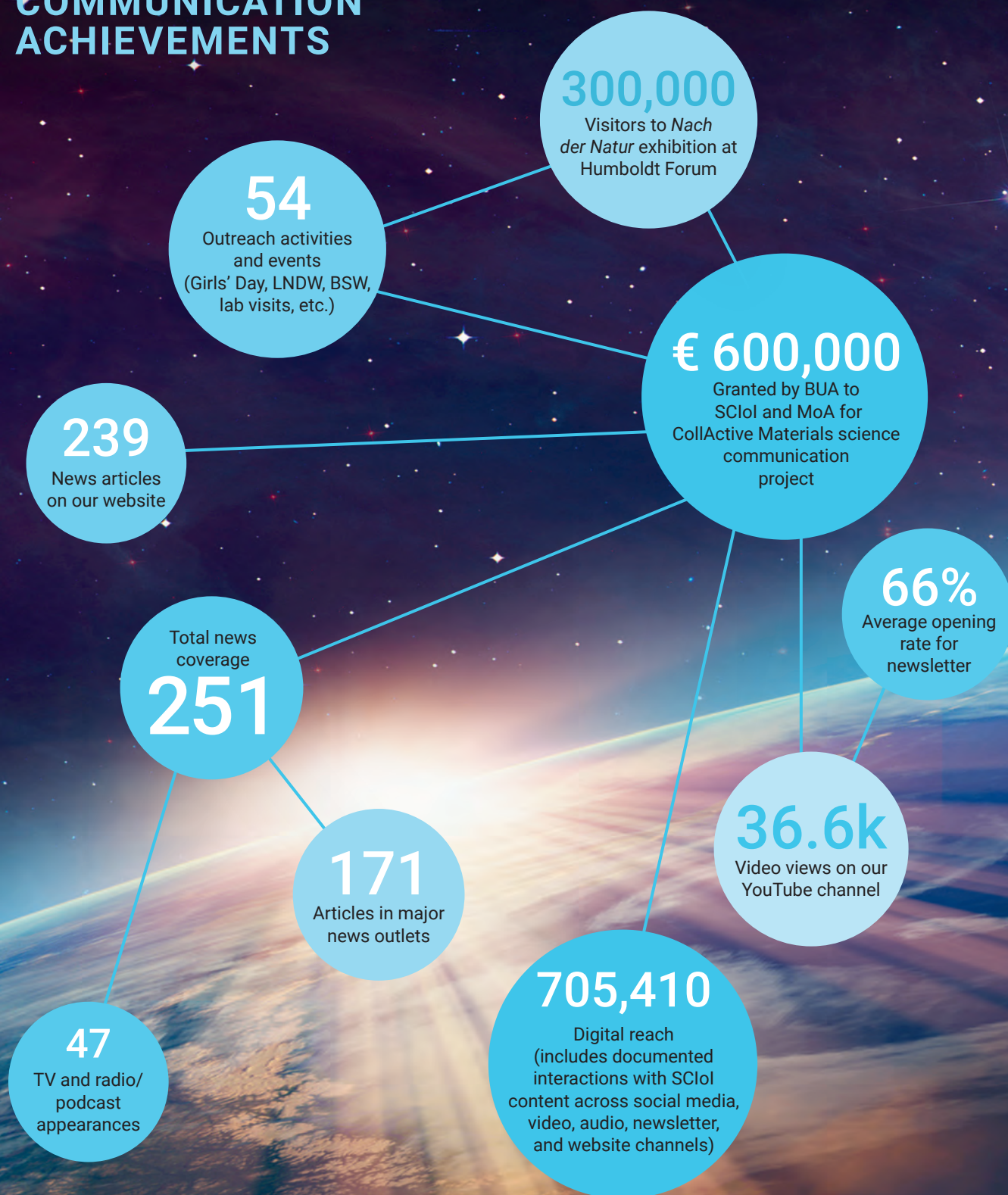
The Scientific Advisory Board

SCloll's Scientific Advisory Board consists of external, highly accomplished scientists possessing extensive interdisciplinary research experience, who advise on scientific matters.

The Ethics Advisory Board

The Ethics Advisory Board is made up of external leading scholars with expertise in the fields of philosophy of artificial intelligence, digital ethics, and robotics. The EAB guides and advises SCloll's research activities.

COMMUNICATION ACHIEVEMENTS



How to Run a Cluster

Managing a Cluster of Excellence goes beyond the routines of conventional project coordination. What begins as a funded research initiative evolves into a complex organizational entity with governance structures, internal dynamics, institutional politics, and collective identity. Coordination is only one dimension of this work. Equally important are mediation, negotiation, and the continuous stabilization of collaboration across disciplinary and institutional boundaries.

BY KATHLEEN WAAK*

When I joined SCIOI as Managing Director in 2021, the Cluster was still in a phase of consolidation. Although it had started in January 2019, and initial research staff had joined in autumn of that year, key infrastructures for collaboration, including laboratories and community spaces, had only been partially established, and would reach full operational capacity only in 2022.

As a result, many conditions that support interdisciplinary research environments (routines, informal exchange, and sustained proximity) had had limited time to develop

before the pandemic further disrupted academic working life. This showed how strongly collaborative research depends not only on scientific intent, but also on material infrastructures and shared organizational practices.

This gradual emergence of infrastructure shaped Cluster management directly. Many coordination mechanisms that are taken for granted in established research environments had to be developed while research was already ongoing. Management was therefore not an additional layer, but part of the continuous production of organizational structures.

* Kathleen Waak (pictured below) is SCIOI's Managing Director. She has years of experience in research management and interdisciplinary coordination.



This dynamic intensifies at scale. With a budget of 42 million euros over seven years, SCIOI operates in a range where size itself is an organizational force. The combination of principal investigators, partner institutions, and research staff generates a density of interactions beyond standard routines. External visibility further amplifies complexity, making coordination an evolving requirement rather than a stable procedure.

Across institutions in Berlin and Brandenburg, this is reinforced by institutional heterogeneity. Differences in administrative systems, governance practices, and organizational cultures turn coordination into a structural challenge. In this context interdisciplinarity does not arise through proximity alone but requires active organizational design through shared environments, co-location, and recurring interaction formats.

In this setting, science management functions primarily as institutional translation. It mediates between scientific practice,

administrative requirements, and institutional logics. Decisions are less about implementation than about aligning heterogeneous expectations into workable arrangements.

Communication, people, decisions

Communication illustrates this very clearly. Since institutional communication occurs along organizational boundaries, SCIOI had to develop its own cross-institutional communication structures for both internal coordination and external representation. Acting as a mediating interface between researchers, partner institutions, and external audiences, communication relies in practice on sustained trust and iterative coordination rather than formal authority with university.

Over time, the Coordination Office developed into a substantial organizational unit with more than ten members. Managing it required defining responsibilities while addressing fragility caused by temporary contracts and staff turnover. Continuity had to be actively produced through documentation, routines, and ongoing exchange, reflecting a structural tension between long-term expectations and temporary organizational conditions.

* Konstantin Olschofsky is SCIOI's project manager.



The TU Berlin's MAR building, home to SCIOI's headquarters.

Collaboration and exchange

International and national scientific collaborations and exchanges are central to SCIOI. The Cluster hosted more than 50 internationally renowned invited experts and disseminated its research at national and international conferences. Summer and Winter Schools and the Global Scientific Exchange Program with the African Institute for Mathematical Sciences (AIMS) enabled advanced research training and PhD pathways for outstanding students from the Global South.

Collaborations include the Bernstein Center for Computational Neuroscience (BCCN), which has been at the forefront of brain research for more than 20 years, the DFG Research Training Group Sensory Computation in Neural Systems, the Einstein Center for Neurosciences, the Berlin School of Mind and Brain, BIFOLD, the Big Data Value Association (BDVA), and the Robotics Institute Germany (RIG). SCIOI contributes to the International Society for Adaptive Behavior (ISAB) conference series and the organically growing alumni network emerging from successive cohorts of researchers.

Taken together, these connections expanded the range of questions, methods, and training environments available within SCIOI's research activities, extending them into broader academic frameworks.

BY KONSTANTIN OLSCHOFSKY*

Building shared environments

One ambition of SCIOI was to establish shared environments for research across institutions and disciplines. Cluster funding enabled the development of laboratories, technical setups and shared workspaces that integrated researchers across projects and disciplines.

Their establishment required extensive organizational work beyond scientific coordination, including procurement and maintenance of equipment, spatial planning, workflow design, access coordination, and ongoing operational support.

While some infrastructures developed into active collaboration hubs, others remained below initial expectations, showing that shared environments do not automatically generate collaboration but depend on time, routines, and emerging communities.

Nevertheless, these environments have reshaped everyday research practice within SCIOI and continue to inform discussions on sustainable shared infrastructures.

BY KONSTANTIN OLSCHOFSKY

In this context, management takes on the role of an intermediary, positioned between spokesperson(s), executive structures, administrative bodies, and the scientific community. Decision-making is rarely linear, so what matters is the ability to negotiate workable compromises between competing expectations, disciplinary cultures, and institutional constraints.

Our internal funding procedures made these tensions visible in practice. Principal investigators evaluate and decide on proposals submitted by their peers within the Cluster. While this peer-based model enables relatively efficient decision-making, it also raises recurring questions of fairness, recognition, and resource distribution. Because not all proposals can be funded, decisions are necessarily selective and embedded in close professional relationships. The outcomes of these evaluations also have feedback effects: Both successful and unsuccessful applications influence subsequent patterns of participation and engagement. Sustaining legitimacy therefore depends on transparent criteria, careful communication, and continuous trust-building.

Right: Organizing events for the public at SCIOI. Far right: Researchers and staff meet in the Team Space.



Differences in disciplinary working styles add complexity. Some groups operate with structured planning logics, others with iterative approaches, and without active mediation, this would lead to fragmentation. The Cluster therefore established recurring formats to synchronize interaction without enforcing uniformity. Examples include formats such as the yearly Scientific Networking Days and the SCIOI Fair 2023, which function as coordination infrastructures that support alignment while preserving disciplinary specificity.

Lessons for the future

Over time, it became clear that formal organizational models such as project plans, reporting structures, and governance charts provide only provisional orientation as the Cluster evolves. This applies equally to infrastructure and resource planning. External disruptions such as the Covid-19 pandemic and an IT incident at TU Berlin affected operations, while procedures across institutions proved slower and more complex than anticipated. Even the negotiation of a joint cooperation agreement extended over several years, long after collaboration had become routine.

During the runtime, questions of sustainability arose in the implementation of long-term, field-developing research structures. Laboratories and workshops can be established



through Cluster funding, but their continuation and institutional embedding depend on processes that extend beyond the funding period.

Quality assurance posed similar challenges, as formal reporting mechanisms are insufficient in interdisciplinary settings where research cultures and standards differ. Oversight depends as much on exchange and shared understanding as on formal evaluation. Earlier and more structured data management would likely have reduced some of these frictions.

What proved valuable was the exchange with other Clusters and consortia. Many challenges reflect broader structural conditions of large collaborative research within the Excellence Strategy. This also highlights the increasing professionalization of science management as a distinct organizational function.

The work behind the science

Managing a Cluster of Excellence ultimately means enabling an organization to function under conditions of complexity, uncertainty, and continuous change. It requires balancing flexibility with structure, mediating between institutional logics, and sustaining cooperation across heterogeneous actors. Scientific output is the visible result, but it depends on the organizational work that makes large-scale collaboration possible. ●

Fostering cultural change

Clusters of Excellence operate within existing university systems while introducing new organizational and collaborative practices. Through the establishment of a Coordination Office, SCIOI developed integrated support structures that connected researchers, university administrations, and partner institutions, enabling continuous and cross-contextual forms of collaboration.

Changes in academic practice were further reflected in the establishment of new professorships in Machine Learning (HU), Computational Psychology (TU), Collective Information Processing (HU), and Learning and Intelligent Systems (TU), as well as the Einstein Foundation professorships in Artificial Intelligence (TU) and Computational Psychology of Intelligence (HU) which provided long-term institutional anchoring for interdisciplinary research agendas.

In parallel, structured education formats for PhD and Master's students, together with Summer and Winter Schools, shaped successive cohorts of researchers that carry interdisciplinary research practices into subsequent academic environments, indicating a gradual diffusion of new forms of scientific collaboration and training beyond the Cluster. *BY KONSTANTIN OLSCHOFSKY*

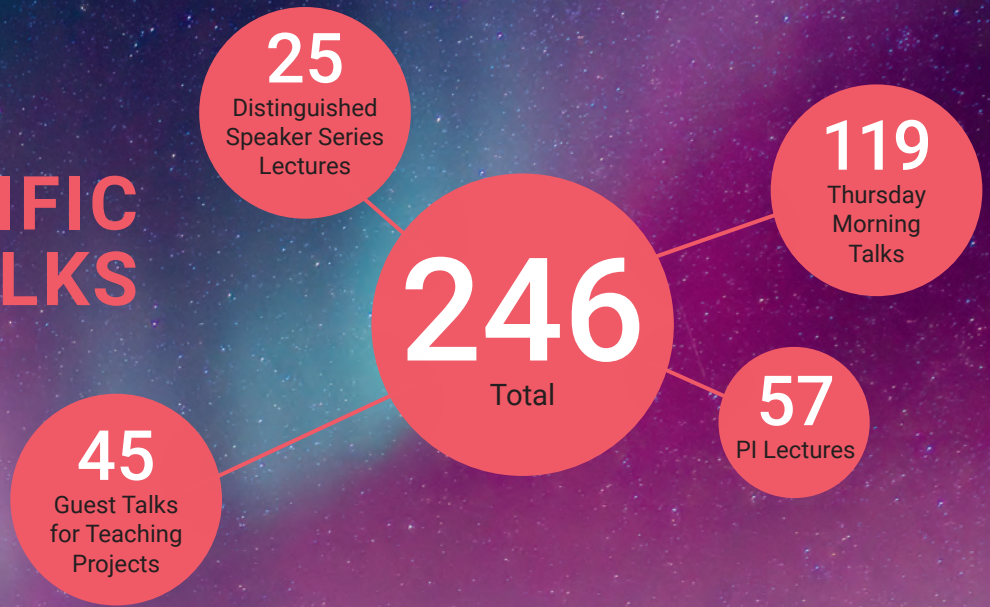
RESEARCH



PEOPLE



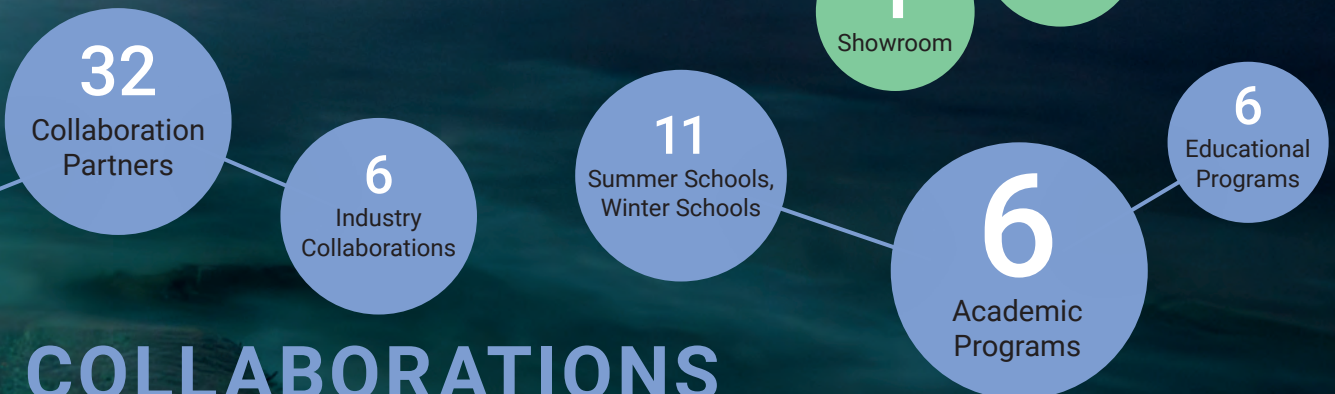
SCIENTIFIC TALKS



INFRASTRUCTURE



COLLABORATIONS



Saved by the Cockatoos

How do you efficiently write for a group of readers that puts policy makers, biologists, philosophers, roboticists, and the regular science enthusiast under the same roof? Is it just a matter of simplifying concepts and removing all the hard bits? Not exactly.

BY SOLVEIG STEINHARDT



One of the cockatoos that were part of one of our projects.

Every time I set out to translate a scientific paper into something wider audiences will understand and, hopefully, appreciate, the image of an accordion immediately springs to my mind. Anything that's not necessary for the story can be cut and shortened, while whatever is more technical but still necessary requires expanding. For me, this compressing and expanding is what science communication is all about. But there are other elements too.

For instance, you have to make sure to pick the right examples, those that speak to everyone, and present them well so audiences will feel invited. While it may be common sense for a roboticist to use “spur gears” as a metaphor for principles, not every psychologist, geologist, or even science journalist will know that they are “toothed wheels that interact with other toothed wheels to transfer rotational force and motion.” Writing for many different readers is about making selections and choices, and making sure nobody is left behind.

The challenge is not just about speaking to students, or to the science lover at the Berlin Science Week: at our Cluster it's also about fostering interdisciplinary communication. As Jens Krause wrote a few pages ago (p.26), interdisciplinarity is about being willing to listen to others and finding a common language to communicate. If we look at it that way, we realize that science communication is not just a way for science to reach the public, but also a way to take down walls between the disciplines and accelerate research.

When SCIOI was first founded, we began developing a podcast on intelligence together with researchers from different disciplines. In the months that followed, the interviews with experts from different disciplines, the writing process that preceded every recording, and the decisions around sound and visual identity became a training ground for interdisciplinary conversation. In editing and post-production, we worked to make complex ideas accessible



A recording session for our podcast, *Punching Cards*.
Right: A display of materials and intelligent objects
on show at a CollActive Materials event in 2022.



to a broader audience without simplifying them away, through narrative linking and careful structuring of explanations within the episode itself. The aim was to reach listeners in everyday contexts, such as during their commute, so we wanted to keep things easy and relaxed while preserving scientific depth.

When we talk to journalists, things are a little different. Here too, you've got to keep it simple because no matter how many scientific qualifications your science journalist has (mind you, not all science journalists are scientists), chances are they're not going to be experts in exactly the discipline you are writing about. You've also got to present your news well, so journalists can pick and choose what they want to use and what they want to leave out. That's why you want to provide them with a pre-cooked story that contains all the important details, but is also understandable, new, and newsworthy.

To complicate matters a bit, different newswires have different preferences: The big international newswires like *EurekAlert!* encourage a simple, good-for-every-journalist language with a bit of a storytelling component. If the journalist needs more details, they will contact the scientists directly. On the other hand, as I experienced during a very interesting panel discussion at the Forum Wissenschaftskommunikation, German science wires prefer to have it all, right from the start: the storytelling, the facts, and even a more

in-depth, more technical section, so the journalist can work independently. Adapting a press release to the different press cultures adds a layer of challenge – and excitement, too.

However, not everything can be summarized in writing; in 2021, we launched CollActive Materials, a science communication experiment generously funded by the Berlin University Alliance, and we had to connect the very-far-away disciplines of two very different Clusters: ours, with 12 disciplines ranging from robotics to psychology and biology, and Matters of Activity, which mixes materials science, philosophy, design, chemistry. In this case, we decided to let the audience do all the work. Through workshops and exhibitions, people from the worlds of research and art, but also individuals from civil society, took part in workshops to imagine and design a future with intelligent materials. The project resulted in many interesting objects, a video, and an exhibition. Sometimes you have to push the boundaries of language to reach new horizons.

Speaking the right language, finding the hook for a story, and selecting when to shorten and when to expand are some of the challenges of science writing. And for good measure, it never hurts to add a pinch of those familiar narrative anchors – of which we luckily have a few around here. Who doesn't love reading about marlin chasing sardines, humanoid robots, fish doing the Mexican wave, or cheeky cockatoos outsmarting their researchers? ●

What Then Must We Communicate?

Before science communication becomes a story, it often starts with a conversation that brings a complex research endeavor into focus. You sit with a researcher and ask questions. What is actually happening here? Why is it important? What surprised you?

BY MARIA OTT

It is tempting to see science communicators as linguistic intermediaries: Researchers produce knowledge, and we make it legible to others. The work, however, starts earlier than that. Communicating science begins with understanding. You enter a scientific

world deeply enough to see its logic, tensions, beauty, perhaps its blind spots. You ask questions until technical details begin to form a larger picture. Then you consider how it should travel: through an article, a conversation, an image, a video, or an exhibition. The right words matter. But so do the right formats.

Over the years at SCIOI, I have come to see communication as part of the scientific process itself, not a final layer added once research is finished. It can help researchers clarify ideas, connect people across fields, and allow audiences outside academia to see science as a human attempt to understand the world. We need to constantly move between levels of complexity. You strip an idea back until its structure becomes visible, then carefully return the nuances: the limits, contradictions, and wider meaning. We don't want to pretend that science is simpler than it is. We want to make complexity navigable.

At SCIOI, this was particularly fascinating because the Cluster was built around an enormous question: What is intelligence? Not only artificial or biological intelligence, but the principles that allow humans, animals, robots, groups, and swarms to perceive, adapt, cooperate, learn, and act in uncertain environments. No single discipline can answer that question alone. Each field brought its methods, language, and assumptions. I loved watching ideas move



Science illustrator Malte von Tiesenhausen is busy designing elements for our principles.



Fieldwork at SCIoI: researching decision-making in ice-fishing competitions in Finland, observing marlins in the Atlantic, and communicating with robots.



between disciplines and return changed: an observation from biology inspiring a robotic system, for example, and building that system raising new questions for biology.

Writing about this kind of science became a way of thinking with the research itself. My background in cultural anthropology taught me to listen closely: to notice how people frame their work, where meanings diverge, and how different ways of seeing can enrich understanding. In an interdisciplinary setting, communication can foster togetherness and create the shared language collaborations need. By connecting the dots across projects, communicators help patterns emerge: Sometimes an article, an interview, or an exhibition gives two researchers a reason to begin a new conversation.

The SCIoI Fair in 2023 brought many of these ideas together. In preparing the exhibition, we worked with our researchers to turn their work into demonstrators and visual experiences. We asked: What is the central idea? What should a visitor notice first? What should stay with them after they leave? As the projects took shape alongside one another, something unplanned happened: While presenting their research, our researchers had to situate their work within our wider scientific environment. That shared act of negotiating and communicating brought the Cluster closer together as a coherent whole.

Another example was visualizing the principles of intelligence featured in this book (see p. 60). We wanted an accessible entry point for different audiences: a conceptual scaffold for readers engaging with the research's full complexity. Malte, a magician at visualizing complex

ideas, helped. Creating those visuals required researchers across disciplines to agree on a shared representation. What was essential? What could be simplified without becoming misleading? Which assumptions had remained hidden in specialist language? The result gave readers a way into the research. At the same time, the process forced us to make implicit assumptions visible and distinguish shared principles from discipline-specific interpretations.

These experiences also explain why I care about this work. People often encounter scientific results without seeing the hardships behind them: the failed experiments, technical problems, revisions, uncertainty, and years of work concealed behind a clean graph or clear conclusion.

I come from a fieldwork tradition, and I am drawn to stories that reveal the work behind the science: researchers standing on frozen lakes in Finland, using drones to capture fish swarms from a tiny boat in the ocean, or teaching a robot to draw like a child. These stories are shaped by improvised solutions and persistence, and remind us that scientific discovery is hard won.

Overall, trust in science should not come from presenting it as infallible. It should come from showing why careful research deserves trust: because it is demanding, self-critical, transparent about uncertainty, and willing to correct itself. Science communication helps people find their way into a question. It means connecting data to curiosity, methods to meaning, and findings to the people who worked to produce them. We create conditions in which knowledge can move more freely: between disciplines, between researchers and audiences, between complexity and understanding. The space between these worlds is where the work comes alive. ●

Diversity Beyond Boxes

As scientists, we are constantly challenged to think outside the box, and this is exactly what we have aimed to achieve with SCIOI: redefining and reshaping how we think, test and consider intelligence across different types of agents and behaviors.

BY JULIE OUERFELLI-ETHIER*

* Julie Ouerfelli-Ethier is a postdoctoral researcher who studies eye movement planning in complex visual scenes.

Diversity is therefore the very foundation of SCIOI: diversity of approaches and methods, diversity of disciplines, and essentially, the diversity of people attempting to learn from one another to build more rigorous and enduring frameworks of intelligence. Accordingly, the Equal Opportunity Committee (EOC) has endeavored to foster the essence of SCIOI's diversity to create a workplace where everyone belongs, thrives, and feels seen.

A box is limiting, but thinking outside the box is not easy either. It forces us to reflect on how we view the world, expanding our perspective to see both what the box contains and what exists beyond its outline. It requires constructive and open dialogues, and this is a continuous process, in which questions and answers feed each other. Through the work of the EOC committee, we have attempted to reframe this continuous process into a strategic approach to ensure that no one, standing outside the box, is left behind. We have done so in mainly three ways: 1) with a comprehensive and intersectional approach, thus without defining boxes or forcing people to define themselves in specific categories. Diversity has multiple meanings, and that is something no box can easily encompass, as we highlighted in our monthly "Diversity Impulse" articles, published on our website. 2) We have encouraged our colleagues to participate in establishing a diverse and equal opportunity workplace that fits their needs. With regular surveys, we have asked colleagues what they need in order to belong, in terms of workshops, events and workplace measures; and 3) We have adopted a personalized and evolving approach by working directly with individuals and by promoting, for example, one-on-one counseling, and support for members in need of accommodations.



The family room at SCIOI.





A SCIOI researcher explains her experiment to a school-aged girl during Girls' Day.

Deconstructing the box is even harder than thinking outside the box, but only by deconstructing can we build a more positive and solid foundation for an inclusive workplace. The ultimate action of the EOC committee was thus to probe our colleagues about what has worked in terms of diversity measures, both inside and outside SCIOI. Based on these responses, we have highlighted ten recommendations that are essential in building a non-restrictive structure that doesn't rely on confining individuals and science to a box, but rather focuses on individuals within a collective. We hope that these recommendations will help other Clusters of Excellence or other research entities support a diverse approach to science, because diverse people bring diverse perspectives and therefore diverse science. ●

The 10 Recommendations

- 1. Promote diversity-relevant aspects in research** to highlight the impact of diversity on research outcomes and, incidentally, discover new dimensions of the studied phenomena.
- 2. Ensure inclusive governance structures** by establishing a committee with members of different academic levels with influence on decision-making processes.
- 3. Support underrepresented groups through intersectional measures** that acknowledge how different diversity dimensions may compound into inequality.
- 4. Foster participatory diversity, equality, inclusivity and belonging measures** by actively seeking engagement and feedback from all.
- 5. Adopt inclusive recruitment practices** by supporting multi-layered and transparent practices that allow candidates to safely ask questions about work culture and expectations.
- 6. Guarantee family-friendly policies** by offering a good work-life balance: flexible work hours, childcare support, child-safe parent-child offices, and part-time options.
- 7. Embed ongoing awareness and learning** by providing educational content on diversity, inclusion, and sense of belonging across different communication channels.
- 8. Ensure access to mental health support** and resources.
- 9. Implement needs-based surveys and accountability processes** on a regular basis and with transparency.
- 10. Foster a sense of belonging among members** with shared offices and communal space, and resources for international colleagues.

People

The study of intelligence is interdisciplinary.
Our community is made up of
145 researchers from twelve disciplines
working at six institutions.



SCIOI researchers and staff at the
Scientific Networking Days 2025.



Selected Grants and Awards

Major Awards



**Member of
the Academia
Europaea**

Jens Krause (2026)



**Humboldt
Preis**

Richard Schweitzer
(2021)



**Werner Heisenberg
Medaille**

Oliver Brock (2024)



**Ursula M. Händel
Animal Welfare
Award (DFG)**

Christa Thöne-Reineke (2026)



**Best Practice
Communication
Award in Animal
Research**

Christa Thöne-Reineke and
Lars Lewejohann (2021)



**EACL's
Outstanding
Paper Award**

Alan Akbik (2023)



**Outstanding
Associate Editor**

(IEEE Robotics
Automation Letters)

Guillermo Gallego (2021)

Grants



ERC Consolidator Grant

Martin Rolfs (2019)



Google Cloud Research Credit Grant

Robert Tjarko Lange



Emmy Noether Grant

Alan Akbik (2021)



G-Research Grant for PhD Students in a Quantitative Field

Robert Tjarko Lange (2023)



NSF AccelNet NeuroPac Fellowship

Friedhelm Hamann



Experimental Labs for Science Communication 2021 (Berlin University Alliance)

Oliver Brock, Dimitri Coelho Mollo, Solveig Steinhardt



X-Student Research Group Grants (BUA)

Doris Pischedda (summer 2021), Pia Bideau (summer 2023), Pia Bideau (winter 2023/2024), Valentin Lecheval (summer 2024)



DFG Eigene Stelle Fellowship

Sean Ehlman



Research Fellow Chair MIAI (Grenoble Alpes, France)

Pia Bideau



SCIoI Research Grants

Nicolas Roth (2022), Aravind Battaje (2023), Mohsen Raoufi (2023)

Other Awards



Best Poster Awards

- VISAPP 2023: Niek Andresen, Katharina Hohlbaum, Christa Thöne-Reineke, Lars Lewejohann, Olaf Hellwich
- ICRA 2024: Heiko Hamann, Mohsen Raoufi, Pawel Romanczuk (Best Workshop Poster Award)
- Berliner PostDoc Days 2025: Tamal Roy
- DPG 2026: Maryam Karimian (Distinguished Poster Prize)
- VNOP Conference 2026: Julia Rodriguez Buritica



Best Paper Awards

- ECVO 2021: Lynn Schmittwilken, Marianne Maertens
- ICRA 2025: Vito Mengers



Travel Awards

- Student Travel Award, CECCO 2023 Conference: Robert Tjarko Lange
- VSS Travel Award: Olga Shurygina



Scout in the Alexander von Humboldt Foundation's Henriette Herz Scouting Programme

Martin Rolfs (2026)



Charafas Prize

Nicolas Roth (2025)



Animal Welfare Award

Dr. Wilma von Düring Research Prize: Katharina Hohlbaum (2019)



Dissertation Awards

- Liselotte Pongratz Dissertation Award: Richard Schweitzer (2022)
- Glushko Dissertation Prize: Lynn Schmittwilken (2026)

People

The SCIOI community is a varied group of scientists with diverse backgrounds that encompass many disciplines. Our researchers also belong to different institutions, including the six partner institutions that constitute SCIOI (Technische Universität Berlin, Humboldt-Universität zu Berlin, Universität Potsdam, Freie Universität Berlin, the Max Planck Institute for Human Development, and Charité – Universitätsmedizin Berlin), as well as other external institutes. Our Cluster consists of principal investigators (PIs), postdoctoral researchers, and doctoral researchers. Student assistants offer help on many projects, while the coordination office team provides administrative, technical, and logistical support.

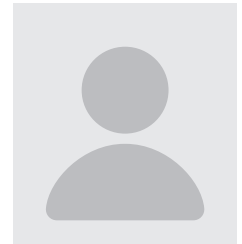
Principal Investigators



Rasha Abdel
Rahman
Psychology



Alan Akbik
Machine Learning



Sabine Ammon
Philosophy



Robert Arlinghaus
Fisheries Science,
Ichthyology



Marcel Brass
Psychology



Oliver Brock
Robotics



Dimitri Coelho Mollo
Philosophy of Artificial
Intelligence



Guillermo Gallego
Computer Vision/Robotics



Verena Hafner
Developmental Robotics



Heiko Hamann
Swarm Robotics



John-Dylan Haynes
Cognitive Neuroscience



Olaf Hellwich
Computer Vision



Ralph Hertwig
Psychology,
Cognitive Science



Alex Kacelnik
Biology



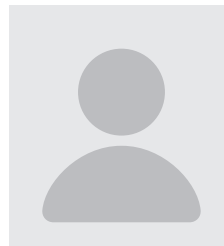
Jens Krause
Biology



Ralf Kusters
Behavioral Biology



Miriam Kyselo
Philosophy of Embodiment,
Cognition



Tim Landgraf
Biorobotics



Rebecca Lazarides
Educational Science



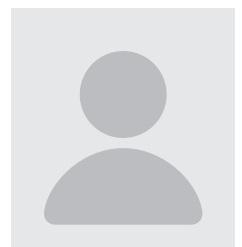
Lars Lewejohann
Behavioral Biology



Falk Lieder
Computational Cognitive
Science



Marianne Maertens
Psychology



Anne Nassauer
Sociology



Klaus Obermayer
Computational
Neuroscience



Thorsten Pachur
Psychology



Michael Pauen
Philosophy of Mind



Niels Pinkwart
Computer Science



Jörg Raisch
Control



Julia Rodriguez
Buritica
Psychology



Martin Rolfs
Psychology



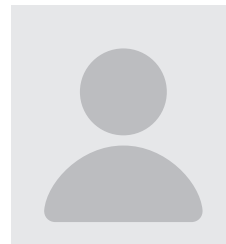
Pawel Romanczuk
Physics



Ingo
Schulz-Schaeffer
Sociology



Henning Sprekeler
Computational
Neuroscience



Josh Tenenbaum
Computational Cognitive
Science



Christa
Thöne-Reineke
Behavioral Biology



Marc Toussaint
Robotics



Alice von Auersperg
Behavioral Biology



Max Wolf
Behavioral Biology

Postdocs



Jinan Allan
Cognitive Psychology



Christoph Alt
Computer Science



Palina Bartashevich
Computer Mathematics



Julia Baum
Psychology



Pia Bideau
Computer Vision, Robotics



David Bierbach
Biology, Biorobotics,
Fish Behavior



Florian Bolenz
Psychology,
Cognitive Science



Dafna Burema
Sociology



Alicia Burns
Biology



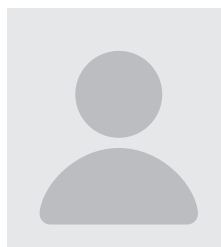
Johann Chevalère
Psychology



Asieh Daneshi
Biomedical Engineering,
Cognitive Science



Dominik Deffner
Evolutionary Behavioral
Science, Computational
Behavioral Science



Raphael Deimel
Robotics



Félicie Dhellemmes
Behavioral Ecology,
Biology



Anna Eiserbeck
Psychology



Sean Ehlman
Behavioral Ecology



Angelica Godinez
Vision Science



Luis Gómez Nava
Physics



Kai Görden
Cognitive Science,
Neuropsychology



Nina Hanning
Psychology



Eitan Hemed
Psychology



Katharina Hohlbaum
Veterinary Science



Anne Jaap
Animal Science



Ashwin Moon-
gathottathil James
Comp. Cognitive Science



Marten Kaas
Philosophy



Maryam Karimian
Computational Cognitive
Neuroscience



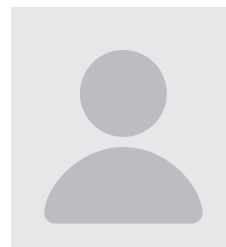
Anna Klenova
Biology



Dimosthenis
Kontogiorgos
Human Robot Interaction



Valentin Lecheval
Collective Behavior,
Ethology



Antje Lorenz
Psychology



Martin Maier
Experimental Psychology



Heinrich Mellmann
Robotics



Paul Mieske
Animal Physiology, Biology



Rainer Mühlhoff
Philosophy



Arianna Novati
Biology, Neurobiology



Julie Ouerfelli-Ethier
Psychology



Doris Pischedda
Neuroscience



Nina Poth
Philosophy of Cognitive
Science



Ole Pütz
Sociology



Apu Ramesh
Behavioral Biology



Tamal Roy
Behavioral Ecology, Biology



Ulrike Scherer
Biology, Evolution of
Behavior, Ecology



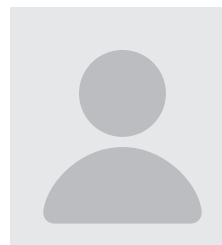
Friedrich Schüßler
Neuroscience, Physics,
Ethology



Richard Schweitzer
Psychology



Yunus Sevinchan
Physics



Nicolas Spatola
Psychology



Alan Novaes Tump
Behavioral Ecology,
Cognitive Science



Olga
Wudarczyk-Markett
Psychology



Yating Zheng
Swarm Robotics



Helene Ackermann
Psychology



Niek Andresen
Computer Vision



Aravind Battaje
Robotics



Manuel Baum
Robotics



Florian Blume
Computer Vision



Mark Boon
Computational
Neuroscience



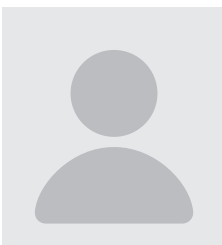
Valerii Chirkov
Computational Social
Science



Furkan Davulcu
Robotics



Danny Driess
Machine Learning



Fritz Francisco
Biology



Jonas Frenkel
Human-Robot Interaction



Marah Halawa
Computer Science



Ole Hall
Computational
Neuroscience



Friedhelm Hamann
Computer Science



Bassel Katamish
Control, Computational
Engineering



Benjamin Lang
Biosciences,
Molecular Biology



Robert Tjarko Lange
Computational
Neuroscience



Anna Lena Lange
Computer Science



Dustin Marlon
Lehmann
Control Systems



Svetlana Levit
Computer Science



Xing Li
Robotics



Vito Mengers
Computer Science,
Robotics



Elena
Merdjanovska
Computer Science



David Mezey
Theoretical Biology



Lea Musiolek
Psychology,
Cognitive Neuroscience



Huu Duc Nguyen
Robotics



Halil Yigit Öksüz
Control Systems



Uroš Petković
Computer Science



Max Ploner
Computer Science



Runfeng Qu
Computer Science,
Machine Learning



Mohsen Raoufi
Computer Science



Nicolas Roth
Computational
Neuroscience



Lynn Schmittwilken
Vision Science



Olga Shurygina
Psychology



Adrian Sieler
Robotics



Heiner Spieß
Computer Science



Sole Traverso
Computer Science



Vincent Wall
Robotics



Magdalena
Yordanova
Computer Engineering



Hae Seon Yun
Computer Science



Oussama Zenkri
Robotics

Research Assistants



Tobias Drewlani
Sociology



Bojana Grujicic
Philosophy



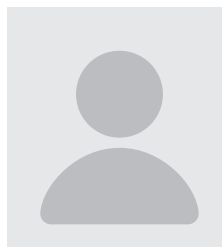
Anja Henke
Educational Sciences



Mattis Jacobs
Philosophy



Pia Kahnau
Behavioral Biology



Olivia O'Connor
Lab Manager at Fish Lab



Bianca Pacini
Physics



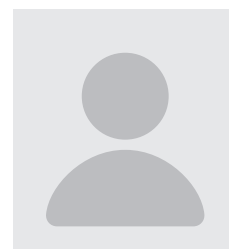
Christopher Schutz
Lab manager at Fish Lab



Martina Vortel
Philosophy



Jacek Wiland
Machine Learning



Simon Weber
Psychology



Pu Xu
Robotics



Under the guidance of the managing director, our coordination office runs all activities in support of research: these include finance and budgeting, project management, press and communication, front office and HR, academic coordination, lab management, IT, and diversity.



Kathleen Waak
Managing Director
(from 2021)



Julten Abdelhalim
Academic Coordination
(to 2025)



Roland Aust
Managing Director
(to 2021)



Sascha Bauer
IT
(to 2025)



Sarah Beckmann
Front Office
(to 2023)



Sabine Bruno
Finances
(to 2023)



Michael Brück
Lab Management
(from 2022)



Sandra Heck
Finances
(2023)



Anne Herms
Finances
(from 2023)



Susanne Hölzemann
Finances and Front Office
(from 2023)



Antje Kaczmarek
Front Office
(to 2025)



Mathis Kaiser
Lab Management
(to 2026)



Serkan Korkmaz
IT
(to 2023)



Lujain Kretzschmar
Diversity and Equal
Opportunities (to 2025)



Marina
Merryweather
Front Office (to 2022)



Zarifa Mohamad
Academic Coordination
(to 2022)



Satyendra Nishad
Lab Management
(to 2024)



Konstantin
Olschofsky
Project Management
(from 2022)



Maria Ott
Press and Communication
(from 2022)



Oksana Rasskazova
Lab Management
(to 2022)



Stephan Rosenzweig
IT
(from 2022)



Philipp Sauer
Lab Management
(from 2025)



Solveig Steinhardt
Press and Communication
(from 2020)



Rolf Struikmans
Lab Management
(to 2024)



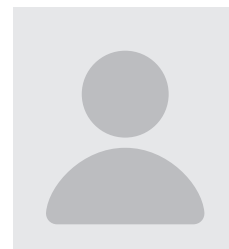
Niki Vavatzanidis
Lab Management
(2023)



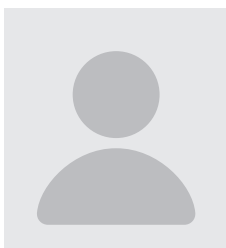
Valeria Becattini
Assistant Communications
(to 2025)



Nicola Chinchella
Assistant Lab Management
(to 2022)



Adrienne Horvath
Assistant Project
Management
(2023)



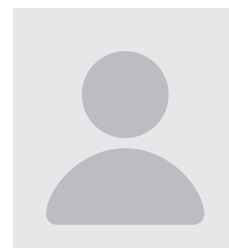
Vijish Kumar Jain
Assistant Lab Management
(to 2025)



Olga Kushinnikova
Assistant Lab Management
(to 2022)



Alexios Nompilakis
Assistant Communications
(to 2025)



Susana Pérez
Blázquez
Assistant Academic
Coordination
(to 2022)



A SCLol researcher
conducts an
experiment in the
Visual Capture Lab.

Publications

Our researchers regularly publish peer-reviewed scientific journal articles and conference papers that contribute to the understanding of intelligence

Research Highlights

Our most notable scientific accomplishments: See pages 32–41 to learn more about a selection of these highlights.

Ackermann, H., Lange, A. L., Hafner, V. V. & Lazarides, R. (2025). **How adaptive social robots influence cognitive, emotional, and self-regulated learning.** *Scientific Reports*, 15(1), 6581. <https://doi.org/10.1038/s41598-025-91236-0>

Battaje, A. & Brock, O. (2022). **One object at a time: Accurate and robust structure from motion for robots.** *IROS 2022*, 3598–3603. <https://doi.org/10.1109/IROS47612.2022.9981953>

Baum, M., Rössler, T., Osuna-Mascaró A. et al. (2024). **Mechanical problem solving in Goffin's cockatoos – Towards modeling complex behavior.** *Adaptive Behavior*, 32(6), 551–562. <https://doi.org/10.1177/10597123241270764>

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Boon, M. N., Andresen, N., Traverso, S., Meier, S., Schuessler, F., Hellwich, O., Lewejohann, L., Thöne-Reineke, C., Sprekeler, H. & Hohlbaum, K. (2024). **Mechanical problem solving in mice [Preprint].** *bioRxiv*. <https://doi.org/10.1101/2024.07.29.605658>

Chevalère, J., Yun, H. S., Henke, A., Pinkwart, N., Hafner, V. V. & Lazarides, R. (2023). **A sequence of learning processes in an intelligent tutoring system from topic-related appraisals to learning gains.** *Learning and Instruction*, 87(2023), 101799. <https://doi.org/10.1016/j.learninstruc.2023.101799>

Chidambaram, S., Wintergerst, S., Kacelnik, A., Nachev, V., Winter, Y. (2024). **Serial reversal learning in nectar-feeding bats.** *Animal Cognition*, 27(1), <https://doi.org/10.1007/s10071-024-01836-y>

Daneshi, A. & Brass, M. (2025). **Does the risk-taking behaviour of a group influence individual risk-taking behaviour?** *Royal Society Open Science*, 12(7), 250200. <https://doi.org/10.1098/rsos.250200>

Deffner, D., Mezey, D., Kahl, B., Schakowski, A., Romanczuk, P., Wu, C. M. & Kurvers, R. (2024). **Collective incentives reduce over-exploitation of social information in unconstrained human groups.** *Nature Communications*, 15(1), 2683. <https://doi.org/10.1038/s41467-024-47010-3>

Doran, C., Bierbach, D., Lukas, J., Klamser, P., Landgraf, T., Klenz, H., Habedank, M., Arias-Rodriguez, L., Krause, S., Romanczuk, P. & Krause, J. (2022). **Fish waves as emergent collective antipredator behavior.** *Current Biology*, 32(3), R123–R125. <https://doi.org/10.1016/j.cub.2021.11.068>

Eiserbeck, A., Maier, M., Baum, J. & Abdel Rahman, R. (2023). **When the philosophical zombie smiles at you – believing a face to be computer-generated affects perception and emotional processing [Conference/Workshop poster].** *ASSC26*

Eiserbeck, A., Maier, M., Baum, J. & Abdel Rahman, R. (2023). **Deepfake smiles matter less – the psychological and neural impact of presumed AI-generated faces.** *Scientific Reports*, 13(1). <https://doi.org/10.1038/s41598-023-42802-x>

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Hamann, F., Gehrig, D., Febryanto, F., Daniilidis, K. & Gallego, G. (2025). **ETAP: Event-based tracking of any point.** *IEEE/CVF Computer Vision and Pattern Recognition Conference (CVPR)*, 27186–27196. <https://doi.org/10.1109/CVPR52734.2025.02532>

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Krause, J., Romanczuk, P., Cracco, E., Arlidge, W., Nassauer, A. & Brass, M. (2021). **Collective rule-breaking.** *Trends in Cognitive Sciences*, 25(12), 1082–1095. <https://doi.org/10.1016/j.tics.2021.08.003>

Lazarides, R., Frenkel, J., Daumiller, M., Dresel, M., Petković, U., Hellwich, O. & Göllner, R. (2026). **Disentangling teacher and lesson variance and their relations to supportive learning environments: A machine learning assessment of teacher nonverbal behavior.** *Journal of Educational Psychology*. <https://doi.org/10.1037/edu0000999>

Lehmann, D., Drebingner, P., Seel, T. & Raisch, J. (2023). **Data-driven dynamic input transfer for learning control in multi-agent systems with heterogeneous unknown dynamics.** *62nd IEEE Conference on Decision and Control (CDC)*. <https://doi.org/10.1109/CDC49753.2023.10383433>

Maier, M., Leonhardt, A., Blume, F., Bideau, P., Hellwich, O. & Abdel Rahman, R. (2025). **Neural dynamics of mental state attribution to social robot faces.** *Social Cognitive and Affective Neuroscience*, 20(1), nsaf027. <https://doi.org/10.1093/scan/nsaf027>

Mengers, V., Battaje, A. & Brock, O. (2025). **AICON: A Representation for Adaptive Behavior [Conference/Workshop poster].** *1st German Robotics Conference*

Mengers, V., Roth, N., Brock, O., Obermayer, K. & Rolfs, M. (2025). **A robotics-inspired Scanpath model reveals the importance of uncertainty and semantic object cues for gaze guidance in dynamic scenes.** *Journal of Vision*, 25(2), 6. <https://doi.org/10.1167/jov.25.2.6>

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Mezey, D., Bastien, R., McKee, N., Zheng, Y., Stoll, D., Hamann, H. & Romanczuk, P. (2025). **Purely vision-based collective movement of robots.** *npj Robotics*, 3(1), 11. <https://doi.org/10.1038/s44182-025-00027-2>

Pacher, K., Bierbach, D., Sevinchan, Y., Vollmoeller, C., Juarez-Lopez, A., Jiménez-Jiménez, J. E., Krause, S., Wolf, M., Romanczuk, P., Arias-Rodríguez, L. & Krause, J. (2025). **Better and faster decisions by larger fish shoals in the wild.** *Science Advances*, 11(31), eadt8600. <https://doi.org/10.1126/sciadv.adt8600>

Pischedda, D., Kaufmann, V., Wudarczyk, O., Abdel Rahman, R., Hafner, V. V., Kuhlen, A. & Haynes, J.-D. (2023). **Human or AI? The brain knows it! A brain-based Turing Test to discriminate between human and artificial agents.** *32nd IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, 951–958. <https://doi.org/10.1109/RO-MAN57019.2023.10309541>

Rat-Fischer, L., Plunkett, K., von Bayern, A. & Kacelnik, A. (2024). **Object play and problem-solving in infancy: insights into tool use.** *Journal of Experimental Child Psychology*, 244, 105957. <https://doi.org/10.1016/j.jecp.2024.105957>

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Schweitzer, R., Seel, T., Raisch, J. & Rolfs, M. (2025). **Early visual signatures and benefits of intra-saccadic motion streaks.** *PLOS Computational Biology*, 21(9), e1013544. <https://doi.org/10.1371/journal.pcbi.1013544>

Taliaronak, V., Lange, A. L., Kirtay, M., Oztup, E. & Hafner, V. V. (2023). **Advancing humanoid robots for social integration: Evaluating trustworthiness through a social cognitive framework.** *32nd IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, 2112–2119. <https://doi.org/10.1109/RO-MAN57019.2023.10309519>

Wall, V., Zöller, G. & Brock, O. (2023). **Passive and active acoustic sensing for soft pneumatic actuators.** *The International Journal of Robotics Research*, 42(3), 108–122. <https://doi.org/10.1177/02783649231168954>

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Publications

SCIOI research consists of many interdisciplinary collaborations on the wide spectrum of intelligence-related themes. Here are all of SCIOI's publications, from 2019 to May 2026.

2026

(15 May)

A

Andresen, N., Wöllhaf, M., Wilzopolski, J., Lang, A., Wolter, A., Howe-Wittek, L., Bekemeier, C., Pawlak, L.-I., Beyer, S., Cynis, H., Hietel, E., Rieckmann, V., Rieckmann, M., Thöne-Reineke, C., Lewejohann, L., Hellwich, O. & Hohlbaum, K. (2026). **Automatic pain face analysis in mice: Applied to a varied dataset with non-standardized conditions [Preprint]**. *bioRxiv*. <https://doi.org/10.64898/2026.02.16.706098>

B

Bartolomei, L., Tosi, F., Poggi, M., Mattoccia, S. & Gallego, G. (2026). **EventHub: Data factory for generalizable event-based stereo networks without active sensors**. *IEEE/CVF Computer Vision and Pattern Recognition Conference (CVPR)*. <https://bartn8.github.io/eventhub/>

C

Coelho Mollo, D. & Millière, R. (2026). **The vector grounding problem**. *Philosophy and the Mind Sciences*, 7(1). <https://doi.org/10.33735/phimisci.2026.12307>

G

Guo, S., Febryanto, F., Sun, L. & Gallego, G. (2026). **Interp3R: Continuous-time 3D geometry estimation with frames and events [Preprint]**. *arXiv*. <https://doi.org/10.48550/arXiv.2603.14528>

H

Henke, A., Harley, J. M., Matin, N., Chevalère, J., Hafner, V., Lazarides, R. & Pinkwart, N. (2026). **Multimodal perspectives on affective dynamics in an intelligent tutoring system**. *Learning and Instruction*, 103, 102310. <https://doi.org/10.1016/j.learninstruc.2025.102310>

K

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Klenova, A. V., Lang, B., Jaap, A., Thöne-Reineke, C., Lewejohann, L. & Mieske, P. (2026). **Female mice in established social groups use different ultrasonic vocalizations during peaceful and aggressive interactions**. *Behavioural Brain Research*, 498, 115904. <https://doi.org/10.1016/j.bbr.2025.115904>

Kohyama, K., Aoki, Y., Gallego, G. & Shiba, S. (2026). **Geometric-photometric event-based 3D Gaussian Ray Tracing**. *IEEE/CVF Computer Vision and Pattern Recognition Conference (CVPR)*. <https://e3ai.github.io/gpert/>

Kroell, L. & Rolfs, M. (2026). **Predictive foveal processing in active vision**. *Annual Review of Vision Science*, 12. <https://doi.org/10.1146/annurev-vision-110323-031112>

L

Highlight Lazarides, R., Frenkel, J., Daumiller, M., Dresel, M., Petković, U., Hellwich, O. & Göllner, R. (2026). **Disentangling teacher and lesson variance and their relations to supportive learning environments: A machine learning assessment of teacher nonverbal behavior.** *Journal of Educational Psychology*. <https://doi.org/10.1037/edu0000999>

Lecheval, V. & Romanczuk, P. (2026). **Future practices of interdisciplinary research in collective animal behaviour.** *Journal of the Royal Society Interface*, 23(234), 20250582. <https://doi.org/10.1098/rsif.2025.0582>

M

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N

Nörenberg, W., Schweitzer, R. & Rolfs, M. (2026). **Rapid masking of saccadic motion results from low-velocity input and is largely invariant to movement amplitude [Preprint].** *bioRxiv*. <https://doi.org/10.64898/2026.04.03.716410>

P

Petković, U., Frenkel, J., Lazarides, R. & Hellwich, O. (2026). **Modeling student engagement in the wild: Analysis from classroom video.** *Proceedings of the 21st International Conference on Computer Vision Theory and Applications – Volume 2: VISAPP*, 2, 439–446. <https://doi.org/10.5220/0014468800004084>

Q

Qu, R., Hall, O., Bideau, P. K., Ouerfelli-Ethier, J., Rolfs, M., Obermayer, K. & Hellwich, O. (2026). **Salience-SGG: Enhancing unbiased scene graph generation with iterative salience estimation.** *IEEE/CVF Winter Conference on Applications of Computer Vision (WACV)*, 1032–1042. <https://doi.org/10.1109/WACV61042.2026.00107>

R

Reiske, P., Boon, M. N., Andresen, N. et al (2026). **Mouse lockbox dataset: behavior recognition for mice solving lockboxes.** *Int J Comput Vis*, 134, 318. <https://doi.org/10.1007/s11263-026-02908-x>

Roy, T., De Faria, J. C. P. & Arlinghaus, R. (2026). **Size-selective mortality evolutionarily alters collective behaviour in response to predation risk in a zebrafish (*Danio rerio*) harvest-induced selection model.** *Journal of Fish Biology*, 108(6), 1865–1874. <https://doi.org/10.1111/jfb.70350>

S

Schakowski, A., Deffner, D., Kortet, R., Niemelä, P. T., Kavelaars, M. M., Monk, C. T., Pykälä, M. & Kurvers, R. H. J. M. (2026). **High-precision tracking of human foragers reveals adaptive social information use in the wild.** *Science*, 391(6784), eady1055. <https://doi.org/10.1126/science.ady1055>

Scherer, U., Ehlman, S. M., Bierbach, D., Pen, I., Krause, J. & Wolf, M. (2026). **Non-genetic inheritance of stochastically induced behavioral individuality in a naturally clonal fish [Preprint].** *bioRxiv*. <https://doi.org/10.64898/2026.03.31.715612>

Scherer, U., Ehlman, S. M., Bierbach, D., Krause, J. & Wolf, M. (2026). **Activity during the first days of life predicts lifespan in a naturally clonal vertebrate [Preprint].** *bioRxiv*. <https://doi.org/10.64898/2026.02.21.707185>

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2025

Highlight Ackermann, H., Lange, A. L., Hafner, V. V. & Lazarides, R. (2025). **How adaptive social robots influence cognitive, emotional, and self-regulated learning**. *Scientific Reports*, 15(1), 6581. <https://doi.org/10.1038/s41598-025-91236-0>

Ackermann, H., Henke, A., Chevalère, J., Yun, H. S., Hafner, V. V., Pinkwart, N. & Lazarides, R. (2025). **Physical embodiment and anthropomorphism of AI tutors and their role in student enjoyment and performance**. *npj Science of Learning*, 10, 1. <https://doi.org/10.1038/s41539-024-00293-z>

Ajuwon, V., Monteiro, T., Walton, M. E. & Kacelnik, A. (2025). **Do goldfish like to be informed?** *Proceedings of the Royal Society B: Biological Sciences*, 292(2047), 20242842. <https://doi.org/10.1098/rspb.2024.2842>

Alies, R., Merdjanovska, E. & Akbik, A. (2025). **Measuring label ambiguity in subjective tasks using predictive uncertainty estimation**. *Proceedings of the 19th Linguistic Annotation Workshop (LAW-XIX-2025)*, 21–34. <https://doi.org/10.18653/v1/2025.law-1.2>

Battaje, A., Hanning, N., Brock, O. & Rolfs, M. (2025). **Depth and interaction modulate color aftereffects in virtual reality [Conference/Workshop poster]**. *ECVP 2025*

Bierbach, D., Lukas, J., Gómez-Nava, L., Francisco, F. A., Arias-Rodriguez, L., Krause, S., Pacher, K., Sevinchan, Y., Romanczuk, P. & Krause, J. (2025). **Collective escape waves provide a generic defence against different avian predators**. *Royal Society Open Science*, 12(3), 241055. <https://doi.org/10.1098/rsos.241055>

B

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Boon, M. N., Andresen, N., Traverso, S., Meier, S., Schuessler, F., Hellwich, O., Lewejohann, L., Thöne-Reineke, C., Hohlbaum, K. & Sprekeler, H. (2025). **Mechanical problem solving in mice [Conference/Workshop poster].** *Computational and Systems Neuroscience (COSYNE) 2026*. <https://doi.org/10.1101/2024.07.29.605658>

C

Cai, N. & Bideau, P. (2025). **Active event alignment for monocular distance estimation.** *IEEE/CVF Winter Conference on Applications of Computer Vision (WACV) 2025*, 2464–2473. <https://doi.org/10.1109/WACV61041.2025.00245>

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D

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E

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F

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G

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G

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H

Hall, O., Qu, R., Ouerfelli-Ethier, J., Hellwich, O., Obermayer, K. & Rolfs, M. (2025). **Modelling visual attention in dynamic scenes under partially competing task demands.** [Conference/Workshop poster]. *Systems Vision Science Symposium*

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What is intelligence? And what fundamental principles link individual, social, and collective intelligence in humans, animals, and artificial systems? This volume draws an overview of seven years of interdisciplinary research conducted by the Berlin Cluster of Excellence “Science of Intelligence” (SCIoI).

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