Thomas Spiegelhalter

Analog to AI Futures: Pioneering SynBio Nexus Design

Concepts, Tools, Workflows, Protocols and Architectural Explorations, 1985-2100

Forewords by Diane Ghirardo and Neil Leach

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Dedication

To lifelong learning and in loving memory of my mother, Elisabeth (1934-2017), and in heartfelt appreciation for the unwavering support of my wife Jeanine Zuula and my daughters, Fenna and Edda, and sons, Jasper and Jonas.

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Foreword

Prof. Diane Ghirardo, PhD[1]

It's a testament to Spiegelhalter's dedication to sustainability, innovation, and the transformative power of design. When Thomas Spiegelhalter first came to my attention, it signalled a new break with how things were done, a fresh and exciting gift that enlivened students and put our technology program on a very different course.

Time has its ways. As he gears up for the next phase, he concludes by setting out the problems he resolved, and more importantly, those he must engage in the years to come. The stakes are incredibly high, for they depend upon our survival as a planet. Spiegelhalter came with the challenge of winning the coveted US Solar Competition as a visiting professor at Carnegie Mellon University. Despite the growing […] that held him back, he never looked back.

This is but a small recognition of what Spiegelhalter stands for in science and technology in the coming years. As understood today, his thesis underwrites the changes in building technology from computer aided design to the rapid building information modelling (BIM) in a trajectory at once compelling and a bit frightening. If then one adds the compelling link of AI design and AI-SynBio strategies, the power of what they can do and his ability to harness them for good rather than evil ends is both reassuring – and frightening in what AI proposes that it will do for us. Spiegelhalter's theory is that with the invention of ChatGPT and other devices, the continuous threat will work wonders in health care, and create significant worries in the rest of the fields.

The meticulous care in health-related fields will be met, on the other hand, by sources such as ChatGPT, where the learners are wildly inaccurate and totally dependent on a system that is quite literally full of misappropriation. Fundamental to all of this is Spiegelhalter's awareness that AI, like every other tool in researching, can give us powerful tools, and in the right hands, can be a way to move forward on such things as driving automobiles, trucks, and even aeroplanes; guide texts and other things, with the sureness that it will be aware of plagiarism.

Whatever the health-related benefits, Spiegelhalter believes that with the right awareness, we can bring to fruition those things that we were unaware of earlier. Through all of these things, through the difficulties of working through them, Spiegelhalter has shown himself to be an optimist par excellence, who believes firmly in what the future holds for us, and a deep commitment to making it come true.

It is with great pleasure that I bring to the attention of others, those who view the work with joy and aticipation. Like his colleague at Cambridge University, it seems that there is in the DNA of those in his field to embrace and celebrate the world around us. Thomas is there.

May 28, 2024

1 University of Southern California, Los Angeles

Foreword

Prof. Neil Leach, PhD[1]

This is a deeply personal history that tracks Professor Spiegelhalter's journey from being a student in Cold War Berlin to a professor in Miami.
Miami is a city also at the centre of attention because of sea-level rise.
The book also tracks an extraordinary story of technologcial developments, from the analogue processes of yesteryear of the latest AI tools.
We can now appreciate how ahead of his time Professor Spiegelhalter was back then.
He was ahead of his time in identifying environmental sustainability as the key issue.
We can also understand how progressive he remains in engaging with AI right now.
Spiegelhalter's vision is clear: The future of design lies in the synergistic blending of technology and nature.
This blending will ensure that our built environments are adaptable, efficient, and resilient.

1 Florida International University (FIU), Visiting Professor at Tongji University, China

Introduction

This research volume thesis, titled *Analog to AI Futures: Pioneering SynBio Nexus Design: Concepts, Tools, Workflows, Protocols and Architectural Explorations Projects 1985-2100,* embodies a forensic examination of my multidisciplinary training and practice of Spiegelhalter Studio, spanning the years 1985 to 2024.

Throughout this work, I explore how utilizing analog-digital tools and design research has been an epistemic force, propelling novel trajectories in my practice, research, and teaching, while also observing the reciprocal influence of these domains. This critical exploration delves deep into the transformative evolution of tool sets—a journey I have personally experienced as an individual and collectively as an active participant in an industry and research undergoing profound metamorphosis.

The narrative intricately weaves my personal trajectory with the seismic shifts reshaping the bio-design research landscape. At the core, this book endeavours to unfurl the magnitude of influence exerted by Synthetic Biology (SynBio), Artificial Intelligence (AI), and Machine Learning (ML) on the evolution of design research practices.

It chronicles a timeline beginning in the 1980's, a seminal period characterised by the nascent stages of these ground-breaking technologies. Yet, it does not stop at the present. It ventures boldly and thoughtfully into the future, attempting to sketch the trajectories of development and disruptions in technologies we may witness by 2100.

I begin my journey with my roots in analog experimental sculpture and design that date back to the '70s. The first chapters delve into my formative years, the time when I was learning professional workflows with traditional, analog tools and techniques in art and design, exposed to culturally and geographically different food, water and energy nexus contexts.

As I sketch out these recollections of the first sculptor training, followed with large-scale Gravel Pit Architecture and Mediatecture infrastructural resource projects, the narrative transitions into the late '80s, marking the radical change from analog to digital tools and algorithms. This period brought my love for multisensory experimental design and pragmatic discipline of architectural engineering into an intricate dance, leading to a unique multidisciplinary and bio-inspired design approach I enthusiastically learned and adopted in the '90s.

The crux of my book thesis lies in the exploration of my German-French-Swiss "Dreilaendereck'' and Italian roots, and the extensive adoption of cutting-edge tools, protocols, and methodologies throughout my career, spanning from 1985 to 2020. This period of my multidisciplinary work and collective research with peers reflects my deep fascination with nature, both living and nonliving.

The efficiency and resilience of these natural systems significantly influenced my multi sensory architectural designs, research, and project realisations. One of my focal points during this time was bionics research workflows, where my objective was to understand, learn from, and emulate nature's principles in design.

In a comprehensive account of the period from 1982 to 1989, I paint a vivid picture of my experiences during the Cold War in West Berlin, where I lived, collaborated , worked, explored, and studied. These experiences were entwined with collective innovative experiments, design hacker night shifts with UdK Berlin peers and friends, and questioning methods, leading to what I later term well documented billion-dollar code syndrome.

My thesis further unpacks the evolution of digital technology in architecture, highlighting the transition from Computer-Aided Design (CAD) to Building Information Modelling (BIM) and the early experiments with evolutionary generative design algorithms from 1990 to 2009.

This part of the narrative delineates my deep-dive explorations into disruptive mediatectures and autopoietic wetware design theories, philosophies, and experimental designs in all scales of multidisciplinary renewable energy, water and food resource infrastructures, buildings and landscapes.

One of the sections in my thesis focuses on an in-depth analysis of my works, offering insights into selected first generation, generative AI-ML assisted architecture projects, tools, and adaptable technologies. It includes a thorough overview of various projects, such as solar-powered mixed-use buildings and solar decathlon competitions.

Here, I articulate my commitment to performance-based sustainability and carbon-positive holistic planning, and the desire to bridge the divide between community design, ubiquitous and adaptable technologies.

As I journey into the later chapters, the narrative deepens with the influence of advancing AI and ML tools on architecture and design practices from 2009 to 2023. It was during this time that I extensively worked on sustainable building design, environmental design optimization, and carbon-positive architecture. By integrating advanced tools, I focused on creating more efficient and sustainable structures.

One of the key themes of my thesis is the importance of interdisciplinary collaboration in achieving carbon-positive design. I argue that by bringing together experts from fields such as AI, ML, SynBio, biology, bionics, architecture, and engineering, it is possible to develop innovative solutions to complex problems. This approach is exemplified in my discussion of generative BIM designed and built case studies in Costa Rica, the US, Japan, China, Africa, and Europe.

Peering into the future, the thesis underscores the anticipated influence of generative AI and ML-assisted design/build processes on redefining the evolutionary boundaries of architectural design. This part of the narrative encompasses various global projects, including carbon-neutral high-rises and smart city designs, as I put these advanced technologies to use for a sustainable and carbon-positive future.

Venturing into the future landscape of design and architecture, my thesis explores the disruptions and evolutions introduced by the convergence of SynBio and AI technologies. It peers into autopoietic wetware coding, quantum realities, the intrinsic nature of mathematics in the natural world and cosmos, and the exploration of the vast universe and our planet's depths through advanced tools.

The thesis concludes with my speculative yet hopeful biomass design manifesto and vision for the future. This vision is for a design and architecture world that thrives in the Natural and Synthetic Biology landscape, powered by continuous learning and innovative thinking. It is the culmination of my experiences, learnings, and hopeful aspirations as I navigate through this evolving landscape of biology inspired design and architecture.

Part I: Foundations and Evolution of Design

Figure 1: This represents my journey spanning 43 years, transitioning from analog to digital, and now engaging across all scales with AI-ML and autopoietic tools, workflows, and protocols. I have been incessantly exploring, learning, and validating concepts from non-living and living systems in the realms of design, architecture, engineering, and urban planning. (Image sources: Thomas Spiegelhalter, 1988 and 2023.)

1. *From Analog to Digital Tools: A Multidisciplinary Design Journey*

1.1. Introduction - How it all began: Origins of Analog Training and Theories, A Legacy Spanning from 1975 to 1988

The fields of evolutionary theory, information theory, quantum computation, biophysics, and synthetic biology have unexpectedly provided answers to future questions about tools, workflows, and protocols in industries such as Arts, Construction, Architecture, and Urban Planning. The disruptive potential of AI-driven language models, quantum theory, and computation has allowed designers and architects to explore new tools, design and theory interventions.

However, questions arise about the trustworthiness of these tools. Who developed their algorithms, and what biases were present during their creation? Who owns them? How transparent are they when they fail? Can they inform us about their limitations?

These uncertainties surround the new technologies and practices in the Arts, Design and in the Architecture, Engineering, and Construction (AEC) industries. Differentiating between reliable and trustworthy tools, software and workflows amidst the hustle of commercial offerings is no easy task [1].

In this given context, in my thesis, "Generative, Evolutionary AI-SynBio Climate Design Tools, Concepts, Workflows, Protocols and Explorations', I present a comprehensive analysis based on my 45 years of experience starting from 1975. Throughout my journey, I have collaborated and learned alongside interdisciplinary artists, designers, architects, and engineers.

Chapter 1 focuses on the historical progression of my training and theories from 1975 to 1988, a period that witnessed the transition from analog to digital tools with the emergence of commercial computer-aided design (CAD), (Figure 1). This chapter explores my utilisation of analog tools, techniques, and workflows during that time. It also highlights the subsequent years marked by the revolutionary Transmission Control Protocol/Internet Protocol Internet (TCP/IP), which revolutionised long-distance data exchanges on a global scale, providing an experimental and collaborative environment for my training, research and work theories, cognition science, and associated philosophies [2].

In my dissertation, I critically reflect on the significant multidisciplinary disruptions caused by the transition from analog to digital design tools and technologies in the ‘80s and ‘90s (Figure 2). These reflections are exemplified through my own designed and built projects and cognition transitions in the following Chapters 4 and 5. But before I proceed with my projects, we need to delve into philosophy, communication, and perception. I believe that theory, philosophy, and cognition science are important for architects, designers and artists because they provide a foundation for understanding the human experience, the natural and built environment, and the relationship between the two.

Chapters 6 to 10 examine how artists, designers, architects, engineers, and contractors and my studio are using information technology to automate their practices. It also contemplates the possibility of architects, and designers being replaced by Automation, Algorithms, Machine Learning, and Artificial Intelligence in the future. Currently, the term *“automation”* is primarily associated with digital manufacturing processes in industries like aerospace, aeronautics, shipbuilding, and automobile manufacturing.

Figure 2: Left two images: Analog tools with water based clay, sculpting. The right two images show digital 3D modelling and 3D printing tools and 3D Printer in any scale depending on the size of the printer.(Photograph. n.d. https://www.tiktok.com/@sculpture.life, https://www.elegoo.com/products/elegoo-saturn-8k-msla-10inch-monochrome-lcd-resin-3d-printer).

These industries operate under different social and financial structures compared to the AEC industry. The AEC industry faces unique challenges, such as stricter regulations, diverse customer preferences, and varying site conditions, while achieving its objectives with fewer professional hours and resources.

For instance, constructing a new car plant typically entails a cost of around 1 billion dollars, and developing a single car model can easily involve over 100,000 hours of engineering work. In contrast, the AEC industry must achieve its objectives with a relatively smaller investment of professional hours, while accommodating stringent local regulations, a broader range of customer preferences, and various site conditions [3].

Scholars have explored the disparities between the design-to-manufacturing processes employed in car production and housing construction. These works, such as "The Productivity Dilemma in Construction: Lessons from the Car Industry" [4], and "Modularization, the Hidden Savior of Sustainable Construction" [5], dissect the variations in process efficiency, waste production, labour cost, and technological utilisation between the two sectors. They advocate for the integration of industrial systems and methodologies to improve construction productivity, resource savings and sustainability, arguing that the current process of bespoke site-based construction is not conducive to the global demand for more efficient and carbon-neutral building design tools, planning methods and manufacturing. These studies underscore the need for transformative changes in the AEC industry, drawing inspiration and lessons from the more mature manufacturing sectors (Figure 3), [4, 5].

Figure 3: Automation themes in the AEC industry are often associated with the social imaginations of practice. The images above show the automated precut of the timber frame for a custom made beach house which was assembled on site in one day and designed by the firm Bakoko in Japan. The method, which is widely used in Japan, uses robotic machinery that can cut wood joints following Japanese traditional intricate carved joinery and customary assembly methods. (Images courtesy of Alastair Townsend).(Townsend, Alastair. *Automation Themes in the AEC Industry Are Often Associated to the Social Imaginations of Practice*. Photograph. n.d.)

Back in 1992, Humberto R. Maturana and Francisco J. Varela described cognition as an ongoing process of bringing forth a world through the actions of coexistence, emphasising its significant social and ethical implications. In this context, it is crucial for me to raise early critical questions about architecture tools, protocols, and workflows that shape creativity, cognition, intelligence, and consciousness [6].

For instance, we can explore the significant differences and similarities between Maturana, Humberto R., and Francisco J. Varela's *The Tree of Knowledge: The Biological Roots of Human Understanding (knowing how we know)* and for example Jocha Bach's theory of Cognitive Science & Artificial Intelligence, or “Artificial Consciousness and the Nature of Reality,” (Figure 4), [7, 8].

Figure 4: This image, created by Thomas Spiegelhalter using Midjourney AI, is inspired by M.C. Escher’s drawing of hands drawing each other, symbolising the circularity of knowledge. As noted by Maturana and Varela (The Tree of Knowledge, 1987), this reflects the dizzying effect of using analysis to examine itself, akin to an eye trying to see itself (pg. 25). (Copyright by Thomas Spiegelhalter, digital artwork, June 19, 2024.).

But before I proceed with my projects, we need to delve into philosophy, communication, and perception. I believe that theory, philosophy, and cognition science are important for architects, designers and artists because they provide a foundation for understanding the human experience, the natural and built environment, and the relationship between the two.

Forty-one years later when I began the journey, we can still ponder the intriguing questions that Jocha Bach asked in 2016: "Who are we?" How does our mind work, and how does it relate to the universe? These questions pose a fascinating riddle that humans continually seek to understand such as Pietro Vesconte Mappa Mundi from 1321 (Figure 5), [9]. The field of Artificial Intelligence and Cognitive Science to build Cognitive Architecture may hold the potential to provide unique answers for my journey through the world of analog and digital worlds.

Figure 5: This image presents the Mappa Mundi, a creation of Pietro Vesconte dating back to 1321, which was incorporated into Marino Sanudo's "Liber secretorum fidelium crusis." Vesconte is renowned as one of the pioneering professional cartographers known to have consistently signed and dated his works. His innovative approach was among the few in Europe before the 14th century that capitalised on the capabilities of cartography and implemented its techniques creatively. This is evident in the world map he crafted circa 1320, which exhibited unprecedented precision in depicting the contours of lands surrounding the Mediterranean and Black Sea. This accuracy can be attributed to his utilisation of portolan, or nautical, charts. Characteristically, Vesconte's world maps featured a circular design with East at the top. (uintern, Detlev. *World Map of Pietro Vesconte. Oxford, Ms. Bodl. Tanner 190, Foll. 203 V-204 in Marino Sanuto's Liber Secretorum*. Photograph. December 2019.)

To summarise some of the main points of comparison and contrast between the two theories, Maturana and Varela's theory of autopoiesis emphasises that living systems are self-producing and self-maintaining networks of processes that define their own boundaries and identity [10]. They argue that cognition is not merely a representation of external reality but a process that brings forth a world through the interactions of the system and its environment. They also propose that language is not a system of symbols but a coordination of actions that enables social coupling and communication. This concept has found applications in fields such as cognition, systems theory, architecture, and sociology. Luhmann, for instance, used autopoiesis to describe social systems as self-reproducing systems of communication [11].

On the other hand, Jocha Bach's theory of artificial consciousness posits that consciousness emerges from the integration of information and computation in a cognitive architecture. He argues that consciousness is not an inherent property of matter but a process of self-modelling and self-referencing that allows an agent to have a subjective perspective and a sense of agency. Bach also suggests that language serves not only as a communication tool but as a means of creating and manipulating concepts that shape our understanding of reality [12].

Some possible similarities between the two theories include their emphasis on embodiment, interaction, and adaptation as vital aspects of cognition and consciousness. Both theories reject the notion of an objective reality separate from the observer and propose that reality is constructed through the cognitive processes of the agent. Intriguingly, both Maturana's and Bach's theories acknowledge the essential role that emotion and motivation play in our learning, creativity, and survival mechanisms. However, distinct differences between the two theories emerge upon closer inspection.

Maturana and Varela perspective tilts towards understanding cognition and consciousness from a biological and phenomenological stance, while Bach's viewpoint is centred more around the computational and engineering facets of artificial intelligence and artificial consciousness. Furthermore, Maturana and Varela approach the matter from a comprehensive, systemic angle, whereas Bach's viewpoint leans towards a more segmented and hierarchical structure.

Additionally, Maturana and Varela's approach is characterised by its descriptive and explanatory nature, while Bach's tends to be more prescriptive and generative. In Joscha Bach's hypothetical Psi architecture, expectations play a crucial role in modulating both certainty and competence, shaping how an agent processes information and executes actions by adjusting its internal confidence and perceived ability based on predictive feedback (Figure 6), [13].

Given the juxtaposition of Maturana and Bach's theories, several questions emerge about the influence these theories could have on my cognitive development as a 16-year-old apprentice sculptor, particularly in the specific context of my training with tools, workflows and communication, culture, and society. Specifically, how could my vocational training, enriched with analog tools, workflows, methodologies, and theories from my evening high school curriculum, have influenced my cognitive growth and skill acquisition?

To deepen the exploration, it is necessary to note that cognition refers to the mental process, like a wizard of consciousness (Figure 7), through which we gain and comprehend knowledge, enabled by our thoughts, experiences, and senses. This process encapsulates diverse aspects of thinking, including memory, attention, problem-solving, creativity, and language use.

Cognition develops throughout our lives, but it undergoes significant changes during adolescence as the time-lapse brain and the synaptic spurt diagrams in (Figure 8) show [14]. According to Piaget's theory of cognitive development, a sixteen year old is in the formal operational stage, which means they can think abstractly, logically, and hypothetically [15]. They can also use deductive reasoning and test their ideas systematically.

A sixteen year old sculptor apprentice may use these cognitive skills to create original and complex art and design works that express their ideas and emotions.

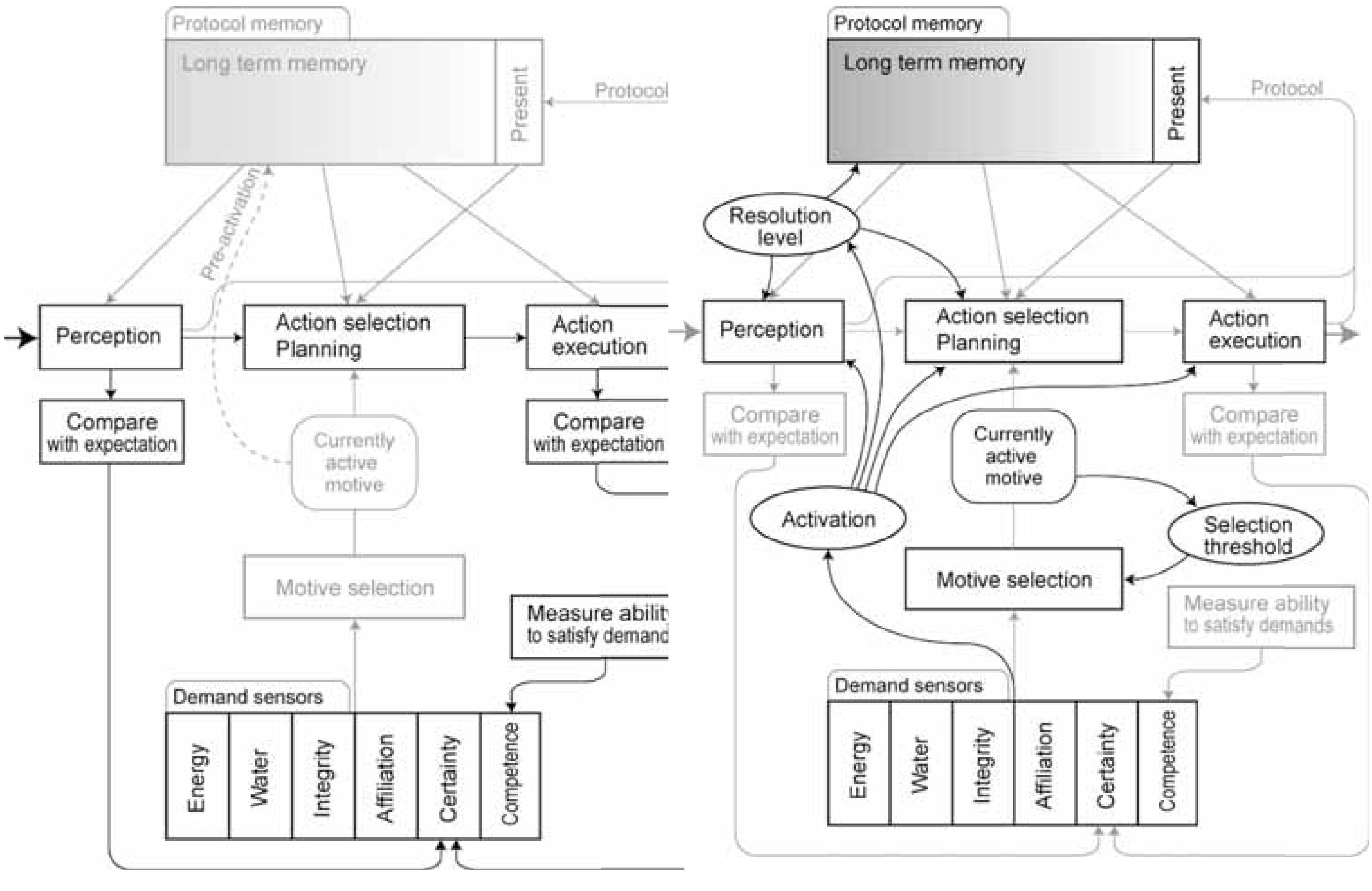

Figure 6: Left image: Psi architecture—the effect of expectations on certainty and competence; right image: Psi architecture—influence of activation, resolution level and selection threshold modulators (Source: Bach, Joscha. Principles of Synthetic Intelligence: Building Blocks for an Architecture of Motivated Cognition. Oxford University Press, 2009.)

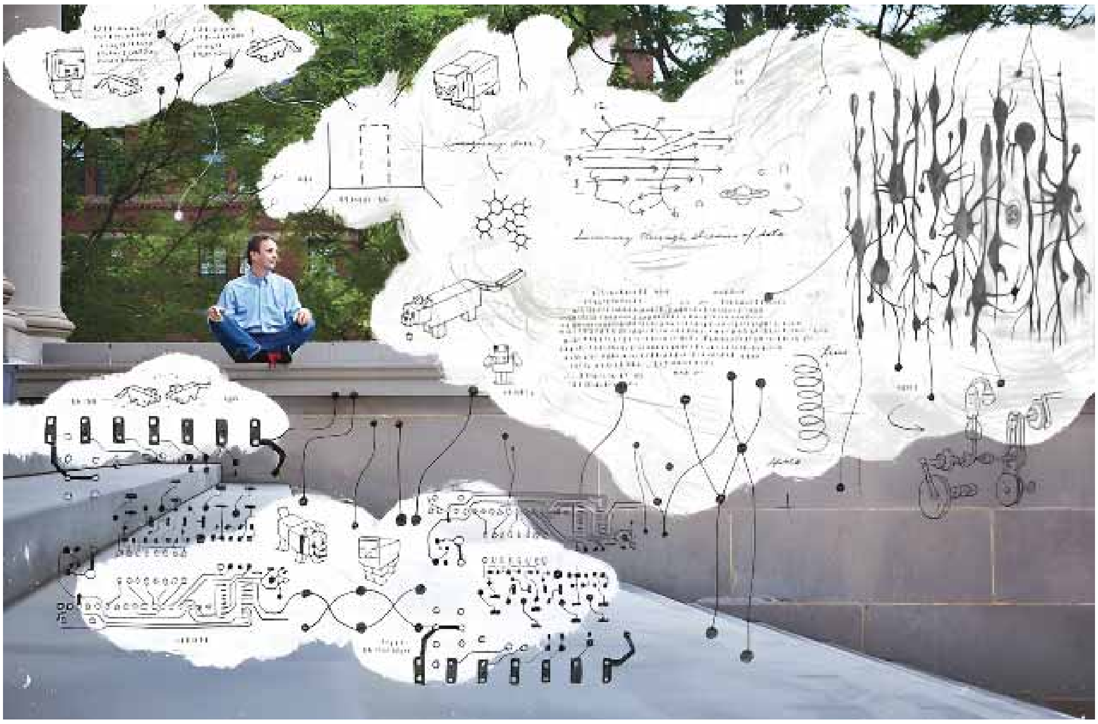

Figure 7: “The Wizard of Consciousness” Joscha Bach’s lifelong quest to achieve strong artificial intelli- gence spurred him to develop a cognitive architecture with a focus on aesthetics and emotion. Photograph by Michael Mcgregor and Illustration by Jonathon Rosen. (Rosen, Jonathon. *The Wizard of Consciousness*. Photograph. n.d. Accessed June 19, 2023. https://www.psychologytoday.com/us/articles/201809/the-wizard-consciousness.)

However, cognition is not only influenced by age, but also by other factors such as genetics, environment, education, culture, societal influences, languages and personal interests. A sixteen year old sculptor may have different cognitive abilities and challenges than a sixteen year old who is not interested in art, design or the natural and built environment. For example, some studies in neuroscience have suggested that arts and design training can improve attention and cognition by strengthening the brain’s attention system, memory and skills development to master tools and executive functions. This may help the sculptor to focus on their work and learn new skills more effectively [16, 17].

Therefore, I argue that the cognition development in the brain of a sixteen year old sculptor is a complex and dynamic process that depends on many factors. It is not possible to give a definitive answer to my questions, but we can explore some of the possible influences and outcomes of my and their cognitive development. In general, the brain of a 16-year-old sculptor apprentice undergoes a complex set of changes and adaptations as they learn to work with various tools, workflows, protocols and design-to-production methods.

Here’s a breakdown of ten selected, different influences or effects that sculpting and designing training might have had on my brain or the brains of colleagues in the same age of early development:

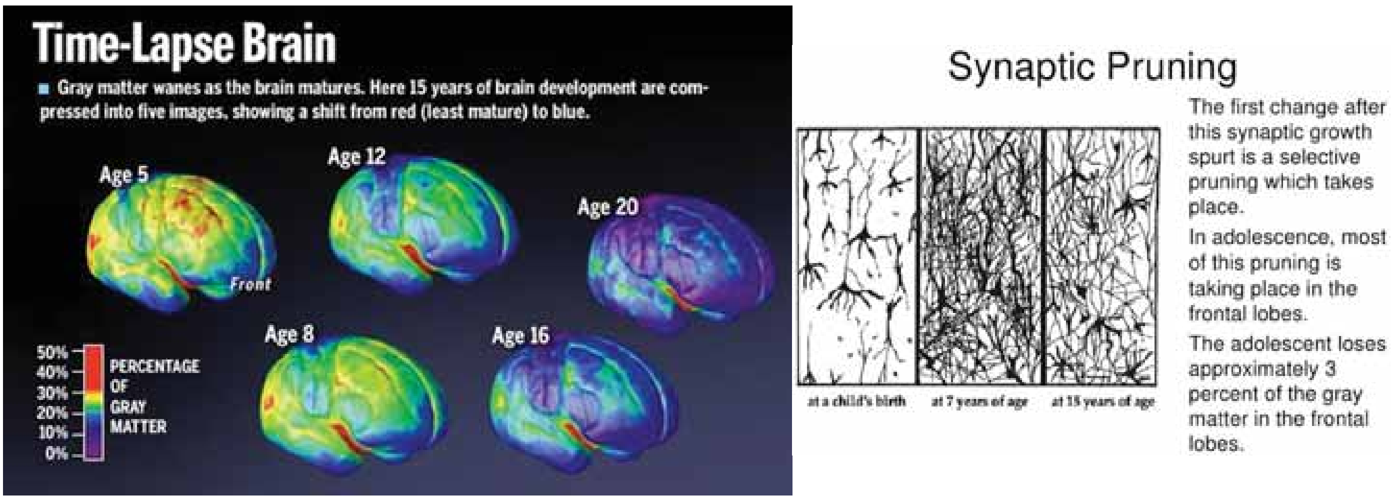

Figure 8: Left image: This MRI-image shows the Time-Lapse Brain. Right image: Synaptic Pruning by Cindy C. Cottle in her Lecture about “The Science Behind the Issue: Adolescent Brain Development (Gogtay, Nitin, Jay N. Giedd, and Leslie Lusk. *Dynamic Mapping of Human Cortical Development During Childhood through Early Adulthood*. Photograph. May 17, 2004.)

1. **Motor Skills:** Sculpting involves intricate hand-eye coordination and fine motor skills. As the apprentice practices, the areas of the brain responsible for these skills (like the cerebellum and the motor cortex) become more refined and efficient.
2. **Spatial Intelligence:** Sculpting is a three-dimensional art. The parietal lobe of the brain, which helps in understanding spatial relationships and manipulating objects, gets a workout when a young artist learns to transform a vision or a design from a two-dimensional sketch into a three-dimensional sculpture.
3. **Visual Processing:** Learning to assess proportions, colours, light, and shadow hones the brain's visual processing skills. The primary visual cortex and associated brain regions become more adept at processing and interpreting visual information.
4. **Creativity:** Sculpting stimulates creativity and promotes divergent thinking. This process engages the brain's default mode network, which is associated with daydreaming, imagination, and creativity.
5. **Concentration and Focus:** Sculpting requires intense concentration and focus, which can strengthen the brain's executive functions. These are managed primarily by the prefrontal cortex and include skills like problem-solving, planning, and attention.
6. **Emotional Processing:** Artistic expression allows for exploration and expression of emotions. This can engage and help develop the limbic system, the brain's emotional processing centre.
7. **Memory:** The act of creating art can boost memory by reinforcing existing neural pathways and creating new ones. Both procedural memory (for skills and techniques) and episodic memory (for the events and experiences around the creation process) may be enhanced.
8. **Resilience and Problem-Solving:** When faced with challenges in the creative process, the apprentice must learn to overcome them. This can strengthen their resilience and problem-solving abilities, stimulating areas of the brain involved in these cognitive functions.
9. **Artistic Appreciation:** As the apprentice learns more about art, aesthetics, and techniques, they develop an enriched appreciation for art. This process can engage various brain regions, including those involved in sensory processing, emotional response, and critical thinking.
10. **Mindfulness and Stress Reduction:** The process of creating art can be meditative and relaxing, helping to reduce stress. This effect can positively influence the brain's amygdala, which is involved in processing emotions and is particularly responsive to stress.

To sum up, my journey of learning sculpting, designing and building and being immersed in critical theories and philosophies from 1975 to 1978, coupled with my time in Venice under the one-year UNESCO Pro Venetia Viva stipend, possibly had a profound impact on my brain. This experience likely fostered and honed an array of cognitive abilities and multisensory skills. These effects wouldn't just assist in my subsequent years of sculpting, designing, and building structures but also likely enriched many other aspects of my life, including my later training as an architect, urban planner and engineer.

Another key point of discussion in this analytical narrative is the general role of philosophers. Which among them have had the most significant impact on the evolution of artists' and sculptors' use of traditional, digital, and augmented reality tools and software, both historically and currently? Indeed, philosophers have had an indelible impact on how artists, architects, and engineers perceive and execute their work, especially as we move into the era of digital, AI and augmented reality tools.

Here are some selected influential philosophers whose theories and ideas have made a substantial impact:

1. **Plato:** (427/428 BC - 348/347 BC) The ancient Greek philosopher's theories about the nature of reality and aesthetics have long been influential in the arts. His theory of forms, in particular, can be seen as an early precursor to the concept of abstraction in art.
2. **René Descartes:** (1596-1650) The Cartesian coordinates system, introduced by this French philosopher and mathematician, is fundamental to geometry, graphics, and navigation in both physical and digital spaces. Descartes' concept of "mind-body dualism" also influenced the thinking behind virtual reality and augmented reality, providing a philosophical basis for the separation of mind (consciousness) from the physical world.
3. **Immanuel Kant:** (1724-1804) His philosophy about aesthetics and the nature of beauty has been influential in the way artists and critics think about art.
4. **Ludwig Wittgenstein:** (1889-1951) His work in language theory and its implications for understanding the world has been influential in fields such as artificial intelligence and cognitive science, indirectly shaping our approach to building digital and computational tools.

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1.1.1. A Sculptor's, Designer's, and Builder's Narratives and Contextual Units: Tools, techniques, and workflows in the 70's

Embark with me on a captivating journey, beginning with my gained experiences as an international sculptor apprentice and builder in the '70s. This journey will transport you through the landscapes of Southwest Germany, Switzerland, French-Alsace, and Italy, introducing you to the tactile world of analogue tools, protocols and traditional workflows. Then later, the journey continues in the '80s with the digital disruptive technology transitions into the age of performance-based, data-driven, computational tool and robotic workflow applications in freelancing, practice, teaching and research in design, engineering, architecture and robotics in the '90s.

The chapters of this thesis will chronicle my exploration and application of autopoietic methods, along with studies of natural systems and their principles as they apply to the arts, design and architecture. The narrative will further delve into the development of design systems inspired by synthetic biology that exhibit bionics, spanning across multiple scales. From the infinitesimal nano scale to the grandeur of macro, the discourse will encompass everything from data-driven infrastructural details, building models, to city-scale designs.

The narratives and design/built case studies shown in this thesis might be undertaken first as a purely philosophical endeavour or with a common platform for epigenetic theory in mind, as the human scale and the respect of the ecologies and resources are at the centre of all arguments in this thesis and envisioning into philosophy and methods of making with tools.

My learning and adaptation approach was constantly driven by synthesising bio-inspired, data-driven, performance-based and carbon-neutral driven science and art as the modus operandi for my work. Any tool served as an extension of my senses for creativity, research, and practice to support biodiversity in environmental design and master planning for architecture and city infrastructures. In addition, fitness testing, reiterating and understanding these approaches allowed me to continuously synthesise innovative tools and protocols into research and practice and vice versa. In particular, my first notable studies and by the Gravel Pit and Cement Industry sponsored research experiments were focused on large-scale post-industrial projects with climate-responsive transformations of abandoned, biotope protected or still in operation existing gravel pit and sand mining infrastructures along the French and German river Rhine area as depicted in Figure 8.

These areas represent until today the artificial second, third and sometimes even fifth natures of landscapes, industrial infrastructure architectures, and machines prone to be transformed or converted into new life and work environments. Located primarily in the southwest German-Swiss triangle, and the French Alsace area, these early projects were deeply embedded in their specific socio-cultural, economic, biome and geological contexts. Critical descriptions of these design and built projects will be discussed in Chapters 4 and 5.

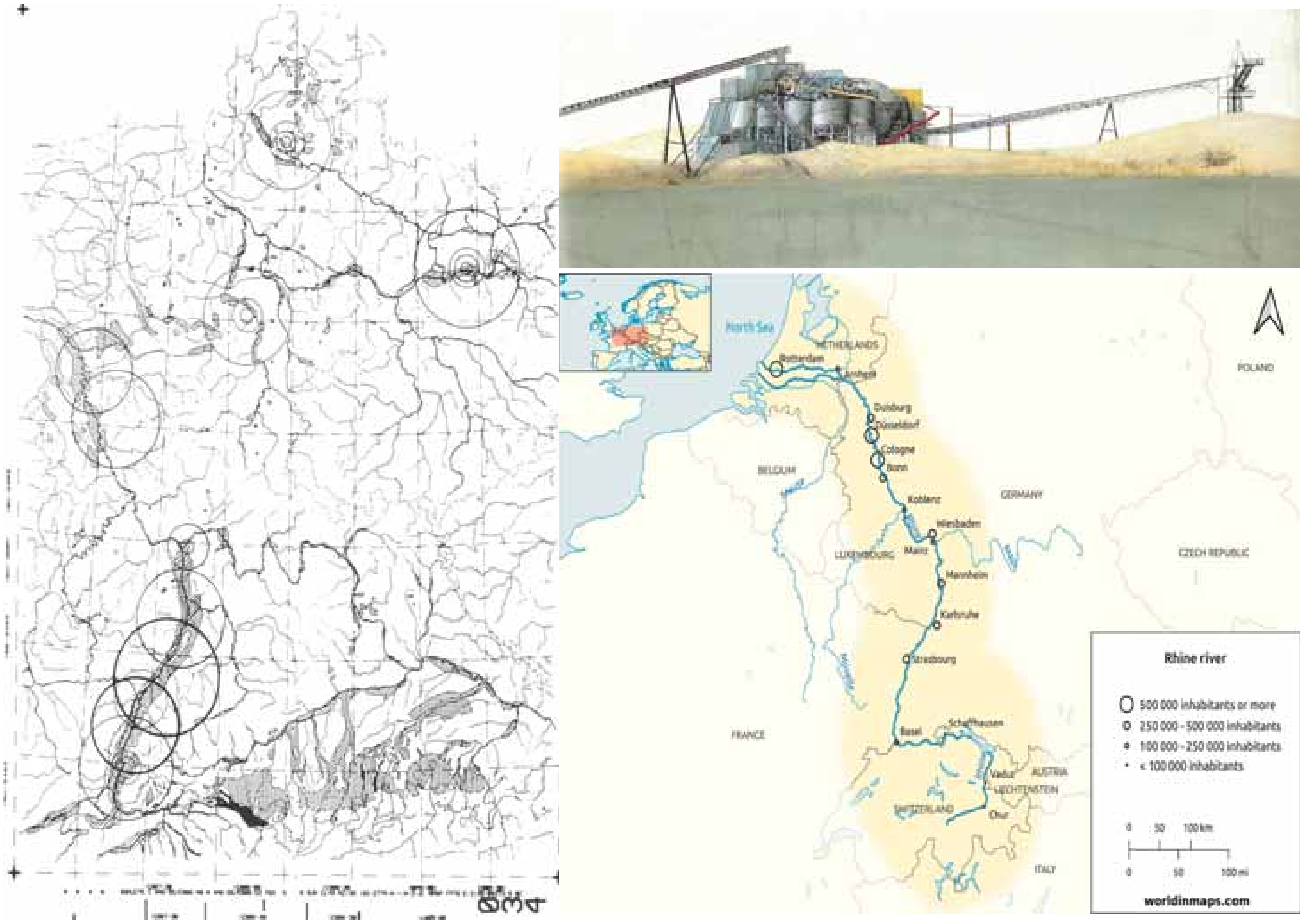

Figure 9: Left: Gravel Pit maps and drawings along the river Rhine from my book Gravel Pit Architecture, 1990, and right image *The Rhine River* map. (*The Rhine River*. Photograph. n.d. Accessed June 10, 2023. https://worldinmaps.com/rivers/rhine.)

Before delving into these experimental research studies and projects, let's journey back to my sculptor and builder beginnings in the '70s and '80s. During my apprenticeship as a sculptor, I was trained using analogue tools to additively work on or subtract form and sculpt, measure, plan, maintain, repair any scale by hand.

The practice and theory of the three year training included hand-, fabrication and mechanical tools and machines, construction physics, chemistry, and material science. It also included trade languages in German, English and Italian, the studies of the anatomy of humans, biology inspired flora and fauna studies for structure, material, matter and form understanding, and the anatomy in modelling and drawing courses of the human body.

There were also multiple history courses about prehistoric and historical times that humanity has always relied on analogue and mechanical tools to help us carry out simple tasks, from building shelters to tools of shaping and fueling the industrial revolution. The First Industrial Revolution used water and steam power to mechanise production. The Second used electric power to create mass production. The Third used electronics and information technology to automate production.

The Fourth and Fifth Industrial Revolutions, representing the merging of the physical, digital, and biological worlds, will be explored in Chapters 6, 9, and 10. This new era showcases the incremental fusion of advances in artificial intelligence (AI), robotics, the Internet of Things (IoT), 3D-printing, genetic engineering, quantum computing, and more. This journey serves as an exploration of humanity's complex relationship with history, the interfaces of culture, technology, and craftsmanship of tools, providing a testament to our resourcefulness and drive to create and build.

Chapters 6, 9, and 10 of this thesis will delve into the Fourth and Fifth Industrial Revolutions, which mark the convergence of the physical, digital, and the natural with synthetic biological worlds. This confluence arises from the rapid advancements in fields such as artificial intelligence (AI), robotics, the Internet of Things (IoT), 3D-printing, genetic engineering, quantum computing, among other emerging technologies.

While many publications have explored the intricate relationship between humans and the historical, cultural, technological and craftsmanship aspects of tools and their historic timelines, enabling us to construct objects and buildings, this thesis does not aim to thoroughly analyse the history of tools from the dawn of humanity.
Instead, it provides only project specific reflections and arguments in Chapters 1 and 2, on the epistemological lineage, the ontology of technological disruptions, and contextual changes concerning the development and use of tools, workflows, and protocol developments throughout the contexts of my studio work and academia.

My journey began with my apprenticeship to become a sculptor and builder from 1975 to 1978. This foundational experience paved the way for subsequent decades of training and exploration, eventually leading me to take on roles as an engineer, architect, and urban planner in the ‘80s. Throughout these shifts and disruptions, I have always held a profound connection to my tools, an emotional attachment or "mud" that I believe is indelible. "Mud" is a term frequently used in the realm of human-computer interaction (HCI) [1].

It denotes the emotional bonds we form with our tools, especially those we frequently use or ones that hold importance in our lives or work. This concept was introduced by Donald Norman in his book *The Design of Everyday Things* (1988) [2]. Norman proposed that these emotional attachments stem from the way we use tools to express our identities and values. Our tools can provide us comfort and security, particularly when we heavily rely on them.

This concept of "mud" has helped explain various phenomena within HCI, such as why people cling to outdated computers or resist adopting new software. It also influences the design of tools, encouraging the creation of emotionally engaging elements like play or humour. "Muds" can be powerful influencers in our lives. They can drive us to work harder, ignite our creativity, and enhance our life enjoyment. As HCI designers continue to explore the concept of "mud," they can potentially create tools that foster a positive impact on people's lives. Occasionally, I enjoy creating “mud boards,” “mud collages,” or “mud photos” to display my favourite tools. Figure 9 shows a collage of various hand tools that have accompanied me throughout my life.

I even went as far as shipping my sea containers full of them from Germany to the US in 1999. This emotional attachment isn't just about the tools themselves, but it also relates to memories and our inherent dependence on prosthetics, whether it's due to a physical loss or our desire to enhance our capabilities.

Great minds like Paul Virilio, Jean Baudrillard, and Vilem Flusser have argued that we, as humans, are continually designing prosthetics for every aspect of our existence, and inevitably, we become dependent on them. To me, it's not just about the tools or prosthetics, it's about the emotional attachments or "muds" that we associate with them, which serve as an integral part of our identities, memories and lives.

Let's dive into the beginning narratives: Following my 1977 apprenticeship as a sculptor in stone, wood, and additive materials such as recycling plastic, bronze, aluminium, and brass, utilising analog tools, additive and subtractive fabrication methods, and pointing machines in Freiburg, Southwest Germany, I was privileged to receive a stipend from the UNESCO "Pro Venetia Viva Foundation" in Venice, Italy, in 1978 [3, 4,]. This opportunity afforded me the joy of learning directly from the Masters of Italian culture and understanding the fascinating intertwining of arts and architecture in the unique environment of Venice [5].

Venice, a city constructed on over 100 small islands in the Adriatic Sea's lagoon and void of any roads, offered me an unforgettable experience of a water-based society. This exposure to such an amphibious environment would serve as invaluable insight for my future design analysis, site studies and scenarios in Fiji, the Americas, Australia, Asia, Bremen, Houston, Los Angeles and Miami (to name a few). The "Pro Venetia" stipend was instrumental in enhancing my understanding of the historical unity of Arts and Architecture, which in contemporary times, are often fragmented or separated into distinct units of planning specialisations.

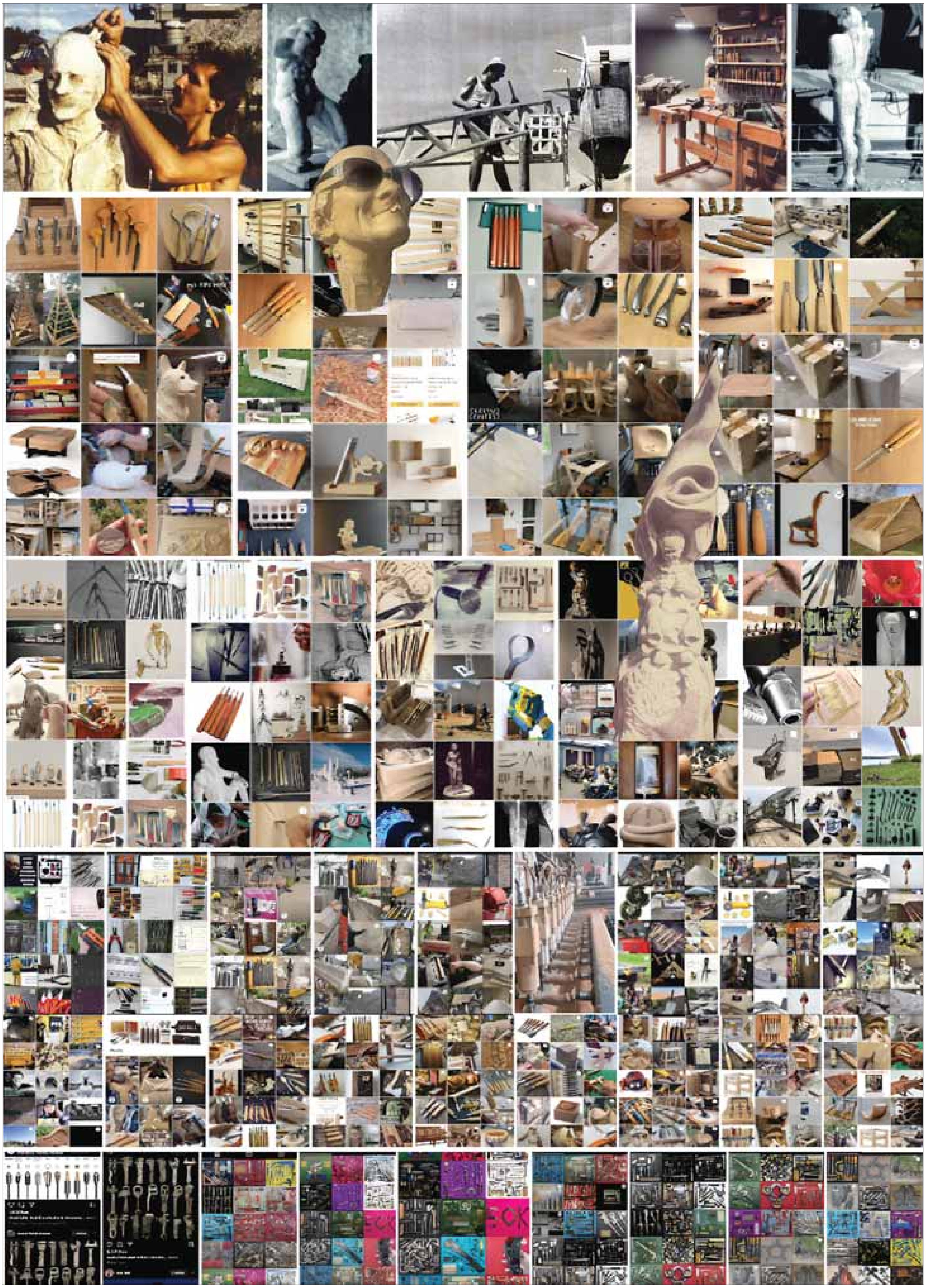

Figure 10: Shows a random collage of various tool sets to develop the skills and knowledge that have accompanied me throughout my life from 1974 to now. (Spiegelhalter, Thomas. A Random Collage of Various Tools through life and training. Photograph. 2023.)

Interestingly and straightforwardly, collaboration has always been crucial in accomplishing larger projects that are typically too large for any individual to handle alone.

In the 21st century, this type of collaboration is referred to as Integrated Project Delivery, which involves the utilisation of shared Building Information master models, often in the form of digital twins.
Building projects not only have functional purposes but also hold social-cultural significance, contributing to the values and livelihood of many individuals.

The nature of these large-scale achievements necessitates collaboration among participants. Different cultures have developed social events and traditions centred around collaborative efforts involved in constructing a facility for the community or an individual within the community. Once completed, a building becomes an integral part of the community, acquiring its own persona and serving as a repository of memories.

Buildings, in their respective settings, have the ability to convey stories and become an intriguing part of the human experience. However, due to the complexity and scale of building projects, the planning, design, construction, and maintenance processes often require the involvement of numerous specialised individuals. The pursuit of efficiency and profitability poses challenges to owners, designers, and contractors as buildings and business processes continue to grow in complexity. Furthermore, successful construction necessitates the cooperation of individuals with diverse skills and interests.

Therefore, this thesis aims to provide an overview of the general organisation of the intricate human interactions involved in the arts, design and building construction. It will delve into selected tools, methods, and protocols employed in the process of creating places, objects, arts and buildings. A prime example of the interdisciplinary approach to inquiry and creativity that has profoundly influenced my work is demonstrated by Leonardo da 1452-1519) and Michelangelo's (1475-1564) extensive repertoire of scientific explorations and creative inspirations.

This thesis aims to provide an overview of the general organisation of the intricate human interactions involved in the arts, design and building construction. It will delve into selected tools, methods, and protocols employed in the process of creating places, objects, arts and buildings. A prime example of the interdisciplinary approach to inquiry and creativity that has profoundly influenced my work is demonstrated by Leonardo da Leonardo Da Vinci's pioneering bionic studies, notably his remarkable drawings in the Codex on the Flight of Birds from 1505, ultimately paved the way for the Wright Brothers' invention of aircraft in 1903, almost 400 years later. These groundbreaking illustrations continue to inspire many, including myself (Figure 10), [6, 7].

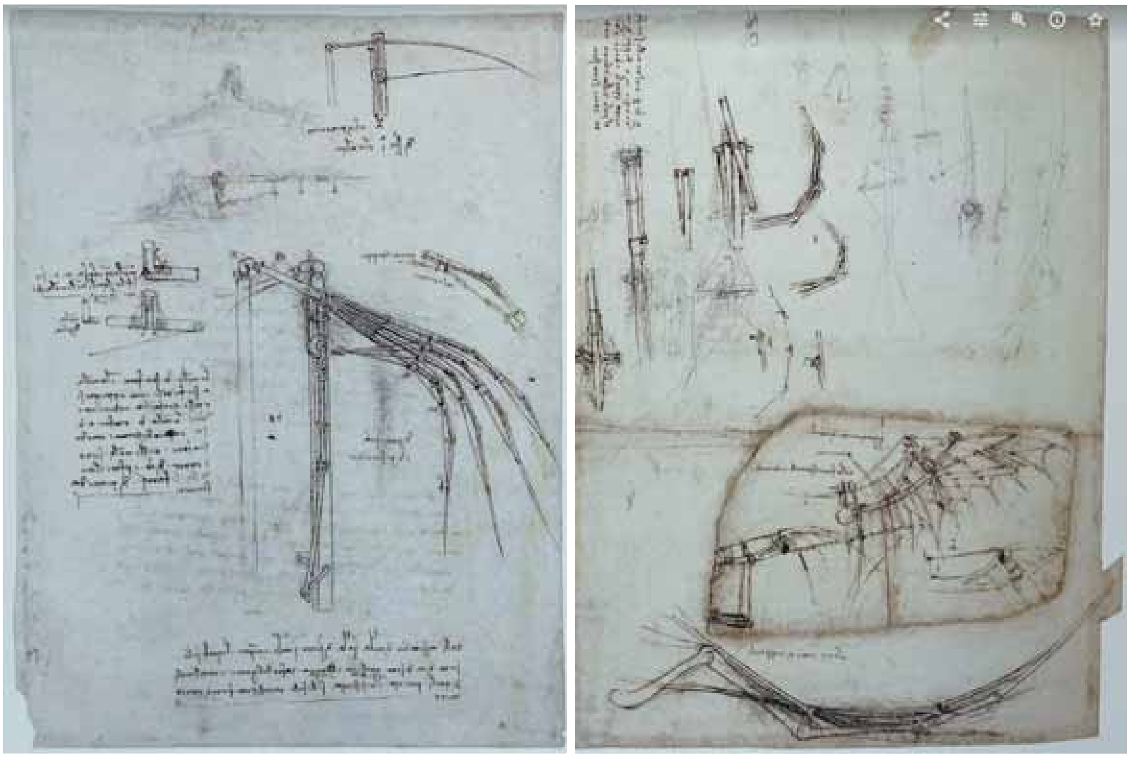

Figure 11: Leonardo da Vinci, Milan, Biblioteca Ambrosiana, Codex Atlanticus. Left Image: Study of the Wing of a flying Machine, 1500-1505. Middle: Sketches and Notes on Flying Machines and Parachutes, 1485-1487. (Kemp, Martin. Leonardo da Vinci: The Complete Paintings and Drawings. Taschenbuch Verlag, 2016. ISBN 978-3-8365-2897-2).

Leonardo's work bridged the gap between unscientific mediaeval methods and our modern approach. His ground-breaking experiments, such as his studies in anatomy and fluid dynamics, far exceeded the achievements of his contemporaries. Beginning with his earliest explorations in Milan and gaining momentum around 1505, Leonardo delved deeper into his scientific inquiries. His range of novel investigation was broad, spanning anatomy, zoology, botany, geology, optics, aerodynamics, and hydrodynamics, among others.

My multiple visits to the Museum of Pathological Anatomy at the Santi Giovanni e Paolo Hospital in Venice, during my UNESCO Venice Stipend (as I lived right around the corner in a rooftop apartment), further stirred my fascination with creative inquiry in fine surgical tool designs and biomimetic engineering. Studying these intricate bionic surgical instruments from historical times catalysed my thinking about large-scale, bio-inspired architectural design mechanics, which would significantly shape my experimental studies at several universities and continued self-education in subsequent decades [8].

Similar to my three-year apprenticeship in Freiburg in Southwest Germany, I have been working - for example- with pointing machines in Venice, Italy [9, 10]. These tools have since been replaced by modern equivalents such as digital laser scanning tools, point clouds, laser point twins, and spatially mobile AI-ML-supported additive-subtractive robots and machines. To illustrate the skills required for the time intensive, analog production workflows before the digital revolution, let me briefly explain how the historic pointing machine, a measuring tool used by sculptors and product designers, functioned.

This tool, despite its name, is not a machine but a device featuring a pointing needle that can be manually fixed to any position and metric in the XYZ location transferred. It got its name from the Italian phrase "macchinetta di punta". The invention of this tool has been attributed to both French sculptor and medallist Nicolas-Marie Gatteaux and British sculptor John Bacon. It was later perfected by Canova [11]. Similar devices were in use during ancient times, especially during the flourishing industry of copying Greek sculptures for the Roman market. The pointing machine was used for creating exact copies of existing sculptures and for replicating models made of plaster, modelling clay, or modelling wax in materials like stone or wood.

For larger-scale models, three-dimensional versions of the pantograph were utilised. For the creation of more substantial models, the pantograph—a mechanical linkage known for its all-encompassing copying ability derived from its Greek roots, - "all, every" and - "to write"—served a crucial role. This device, founded on the principles of parallelograms, was designed such that the movement of one pen tracing an image or model led to identical movements in a second pen [12].

If the first pen traced a line drawing, the other pen would draw a copy, which could be of the same size, enlarged, or miniaturised. Pantographs found application in a variety of duplication tasks such as sculpture, minting, engraving, and milling. The design of the original pantograph lent itself to the creation of structures that could extend or contract in a manner reminiscent of an accordion, forming a signature rhomboidal pattern. This configuration can be found in wall-mounted mirrors, temporary fences, pantographic knives, scissor lifts, and other scissor mechanisms, including those used on electric locomotives and trams. Mobile-programmed 3D robots began to replace sculptor-pointing machines in the early 2000s. The first commercial 3D robot was the 3D Systems SLA-1, which was released in 1988. However, these early robots were very expensive and difficult to use. It wasn't until the early 2000s that 3D robots became more affordable and user-friendly.

In the present day, traditional pointing machines and pantograph techniques have been largely replaced at multiple scales by the digitization process, which incorporates stationary and mobile robots, 3D, laser scanners, and drones that generate cloud points from small-scale objects to entire cities, creating digital twins. Some artists maintain the use of pantographs for drawing or painting enlargement or reduction, while others leverage digital software, scanners, and printers to achieve similar results (Figure 12), [13, 14].

While ancient sculptors relied on technical assistants like pointing machines or pantographs for their creations I had to learn these techniques as a sculptor without assistants in the ‘70s contemporary sculptors have digital alternatives at their disposal. Previously, a successful sculptor might have managed a large workshop team comprising dozens of assistants and students. Today, these human assistants have been replaced by digital counterparts like laser pointing machines, AI-ML assisted and programmed robots, milling machines, CNC, and other subtractive or additive fabrication processes, such as computer-guided router and laser systems that can scan a model and reproduce it in a variety of materials at any desired size [15, 16].

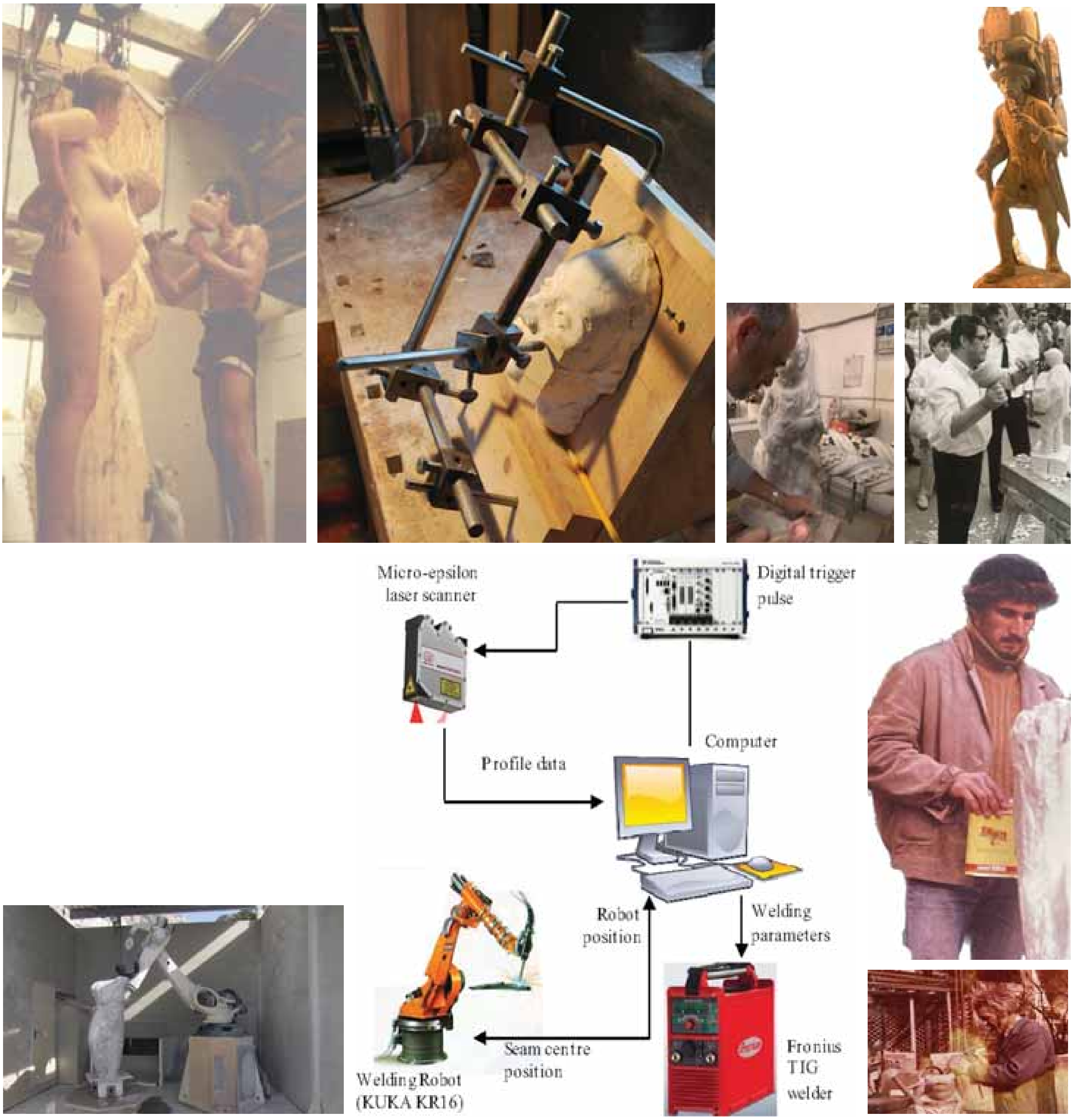

Figure 12: Upper left image: Thomas Spiegelhalter engaged in freeform sculpting of a wooden figure with a nude model in his Freiburg atelier in 1989. The central image contrasts this process with a traditional pointing machine. Far right image: Sculptor Joseph Spiegelhalter is depicted in a freeform sculpting process. Lower left image: ROBOTOR company's 1L robot carving a block of Carrara marble into a Venus figure at their facility in Carrara, Italy (Livesay, Chris. Robots Marble Sculpture in Carrara, Italy. CBS News, Jan. 3, 2023.). Middle image: Robotic principle diagram for welding, which operates similarly to robotic sculpting using G-Code (Phairatt, Manorathna. System Integration Diagram for a Computer Programmed Adaptive KUKA Robotic Welding. Photograph, Dec. 1, 2014). Lower right image: Thomas Spiegelhalter and colleage working with marble tools.

Figure 13 illustrates the evolution of methods used to create wooden carving figures at the Atelier Spiegelhalter in Freiburg. These methods have shifted from traditional copy milling processes in 1990 to modern 3D printing techniques that use multifunctional materials, aided by today's artificial intelligence-assisted fabrication technologies.

The stark contrast between the tools and technology utilised in both approaches is clearly showcased in Figure 13. The 3D-printable functional materials and devices, produced through AI-assisted fabrication. On larger scales, self-learning factories are now used for tasks like automobile or housing manufacturing, which will be discussed in more detail in Chapter 6.4.1.

It's worth noting that the social units involved in the integrated project delivery process in ancient and mediaeval times were predominantly artisans like stone masons and carpenters. As history progressed, these artisans

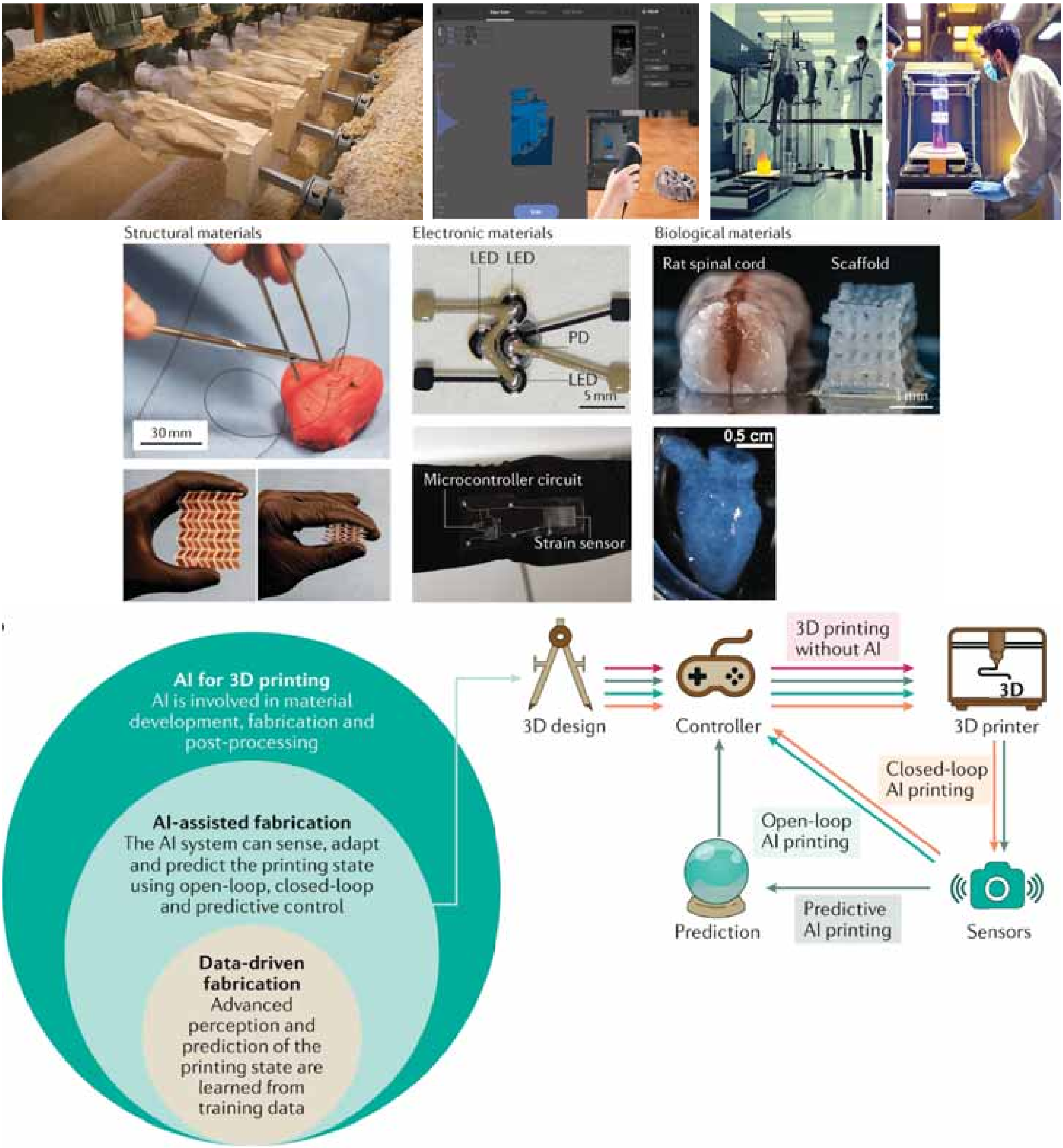

Figure 13: Left top image, A: Production of a wooden carving blank using the copy milling process, Atelier Spiegelhalter, 1990. Middle and left top image: 3D-printed multifunctional materials enabled by artificial-intelligence-assisted fabrication technologies. Image below, B: Overview of 3D-printable functional materials and devices that can be printed with artificial intelligence (AI)-assisted fabrication. Examples of applications for structural materials include a 3D-printed prostate model. (Source: Zhu, Z., Ng, D.W.H., Park, H.S. *et al.* 3D-printed multifunctional materials enabled by artificial-intelligence-assisted fabrication technologies. *Nat Rev Mater* 6, 27–47 (2021). https://doi.org/10.1038/s41578-020-002352)

evolved into today's master builders, architects, and engineers [17, 18, 19, 20].

In the past, there was no definitive separation between the roles of architect and engineer—a distinction that is again becoming indistinct in today's context due to automation, machine learning, and artificial intelligence reshaping the landscape of the Architecture, Engineering, and Construction (AEC) profession.

The term "architect" first appeared in the English-speaking world in 1563, and its origins as a term for a master builder can be traced in Samuel Johnson's 1755 publication, A Dictionary of the English Language: Architect – One who devises a building; a builder. This derives from the Middle French 'architecte,' Latin ‘architectus,’ and Ancient Greek ‘ἀρχιτέκτων’ (arkhitéktōn, “master builder”), from ‘ἀρχι-’ (arkhi-, “chief”) + ‘τέκτων’ (téktōn, “builder”) [21, 22].

In Europe, the roles of architect and engineer were largely synonymous and often interchangeable, differing mainly due to regional vernaculars. Filippo Brunelleschi, one of history's most innovative architects with his discovery of a two-point perspective, is noteworthy in this context. Known for his remarkable contributions to architectural design, he was among the first to be recognized and referred to as a 'gentleman' architect, distinguishing himself from the hands-on craftsman (Figure 14), [23, 24].

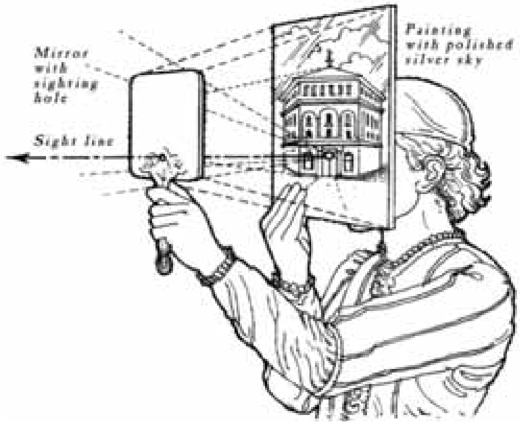

Figure 14: Image, Filippo Brunelleschi and the re-discovery of Linear Perspective in 1415. (Source: Shem Louis "Brunelleschi and the re-discovery of Linear Perspective | COVE (covecollective.org)".) (Louis, Shem. *Brunelleschi and the Re-Discovery of Linear Perspective*. Photograph. October 12, 2020. https://editions.covecollective.org/content/brunelleschi-and-re-discovery-linear-perspective.)

Paper began to be used for drawings in Europe in the 15th century and became more accessible after 1500. Today, traditional 2D drawings are increasingly being replaced by digitally coded, virtual, or augmented reality (VR) representations, and in the near future, holograms, metaverse, and quantum computing are expected to present alternative realities where the constraints of time and speed are altered. Contemporary sketching is accomplished with digital pens, text prompts to images, and various geometric tools, and will soon involve gestures via an optoelectronic Human-Brain-Interface (HBCI) or open AI Chat Generative Pre-Trained Transformer (ChatGPT), launched on November 30, 2022, text prompts that generate renderings, codes, scripts, animations, videos, plans, and models.

Figure 15: Images depict my apprenticeship sculptural work under Joerg Bollin in Freiburg from 1974 to 1977 (left to center), followed by my sculptural human anatomy studies in marble and wood at the Flensburg Werkkunstschule (Art Academy) in 1982. (Images by Thomas Spiegelhalter, 1975 and 1982)

In the 15th century, the advent of linear perspective and innovations, such as the use of different projections to represent a three-dimensional building in two dimensions, along with an enhanced understanding of dimensional precision, all improved how building designs were communicated. However, this was a gradual evolution, and until the 18th century, the design and layout of buildings continued to be managed by craftsmen, barring high-status projects.

In today's world of units and protocols, the practice of architecture, engineering, and urban planning is limited in most developed countries to individuals who have achieved the requisite qualifications, including appropriate education, licensing, certification, or registration with a relevant professional body (often governmental). This usually necessitates a university degree, successful completion of examinations, and a period of training. Moreover, the title of "*Architect*" and its usage is legally reserved for licensed individuals, though derivatives such as "Architectural Designer" are often not legally protected.

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From Craft to Code:
The Evolution of Precision Fabrication Tools

For thousands of years, humans have shaped materials through six fundamental tools and methods, for example: subtracting (chipping stone), forming (pottery), assembling (carpentry), fastening (sewing), finishing (polishing), and removing material (drilling).Throughout history, we've continuously developed tools to refine these methods. Today, digitization and robotics are transforming these tools, leading to exponential gains in accuracy and repeatabilitv.

FORMING

Forming uses mechanical pressure to shape an object into a new form, without adding or removing any material...Mechanized forming includes rolling, extru-ding, erasing, and stretching.

CUTTING

Removing material to form new shapes is also known as machining, milling, sawing, chiseling, and mitering. CNC machines perform a computerized version of cutting.

CASTING

Casting, a 6,000-year-old process, involves pouring liquid into a hollow form and allowing it to become a solid.Computerized casting with synchronized CT scan-ners utilizes precision injecting and grinding to remove imperfections.

MOLDING

Molding is the process of shaping a pliable material within a rigid form, called a matrix, to produce a new form. Machine molded parts have to be carefully designed to allow for flow and cooling patterns.

JOINING

Joining is bringing together two or more forms of similar or different materials by welding, soldering, fastening, taping, riveting, or holting. Robotics easily automate the process of fastening objects.

ADDING

Objects are built up by depositing successive layers of materials. Additive manufacturing, usually known as 3D printing, is essentially a robot precisely depositing layers of a material.

01. METALS

The simple structure of most metals gives them their properties, such as strength, malleability, conductivity, fragility, or weight. Ninety of the 118 elements are metals.

02. ALLOYS

When a metal is combined with one or more other metals or compounds, they create more complex structures with new properties, including strength, durability, ductility, hard-ness, and corrosion resistance.

03. GLASS

Glass is its own state of matter, made when its viscous state is cooled fast enough to produce an irregular, not crystalline structure. It is hard, strong, somewhat elastic, heat absorbent, and of course has optical properties.

04. METAMATERIALS

Metamaterials are engineered to have properties that have not yet been found in nature. Generally made by 3D printing simpler com-pounds, their combined structures provide complex, unexpec-ted behaviors, like getting narrower when com-pressed, or hotter when twisted. With new, user-friendly interfaces, researchers can quickly design many cellular metamaterial structures that have unique mechanical properties.

05. CERAMICS

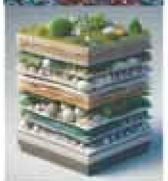
The vast range of ceramic materials are generally hard and strong but often brittle. With high melting points and good insulating properties, they are found in kitchenware and indus-trial applications, bone and tooth re-placements, and super-strong cutting tools. Their fine grains give tiles and cups their brittleness.

06. RECYCLET PLASTICS

Polymers are made from large molecules linked in long, repeating chains. They boast a wide range of properties, from tough (plastics) to pliable (sty-rofoam) to clinging (plastic wrap).

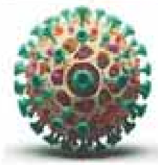
07. SEMICONDUCTORS

Semiconductors, usually made of silicon with added impurities, can conduct electricity under some conditions. That property has been exploi-ted to turn the material into in-tegrated circuits with billions of tiny transistors.



08. COMPOSITES

When two or more materials with different physical or chemical proper-ties are combined, they become a composite. Though still separate, the combined materials have properties that emerge from the interaction: They can be stron-ger, lighter, or less ex-pansive, among other things. They are used for building boat hulls, swim-ming pools, shower stalls, and spacecraft.

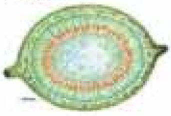


09. VIRUSES

Viruses exist at the border between living and nonliving matter. Consisting of genetic code wrap-ped by an en-closure, they can replicate only in-side the cells of other organisms.

10. SINGLE CELL

Bacteria, amoeba, and other single-celled orga-nisms are the most com-mon form of life on earth. Each cell is a miniature factory that con- verts environmental material into other materials through the metabolism of living.



11. TISSUES

Single cells organized into groups can form or-gans, muscles, and joints, parts of a living orga-nism that are systems on their own.

12. COMPLEX LIFE

The most complex form of materials are living creatures. With intelligence, metabolism, and the capacity to reproduce and change their environ-ments, they are matter with volition.

Figure 16: From Craft to Code: The Evolution of Precision Fabrication Tools. (Copyright Diagram: Thomas Spiegelhalter, June 2024.)