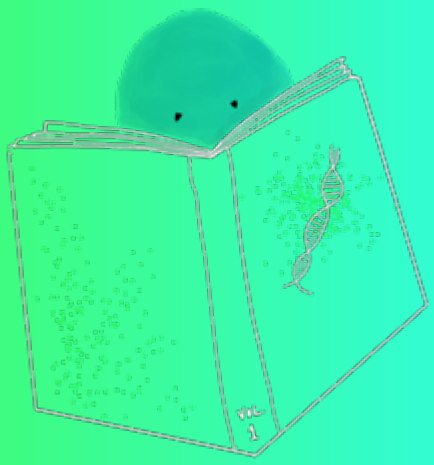
BIOTECHNOLOGY IN COLOUR



An Illustrated Encyclopaedia of Discoveries, Ethics and Science

This book was edited in the framework of the project *BIOASSEMBLER-Integrating bio-inspired assembly into semiconductor manufacturing technology for biosensors*, that has received funding from the European Union's Horizon Europe Research and Innovation Programme under grant agreement 101070589. It reflects the views only of the authors, and the European Union cannot be held responsible for any use which may be made of the information contained therein.

https://bioassembler.eu/

BIOASSEMBLER

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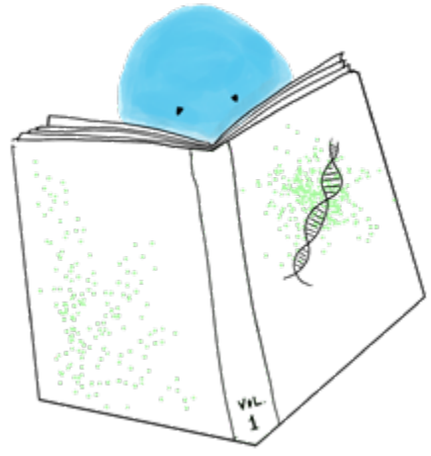

An Illustrated Encyclopaedia of Discoveries, Ethics and Science

Title
Biotechnology in colour.
An illustrated encyclopaedia of discoveries, ethics and science

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NOTE

This book has been shaped by both the content and the process of its creation.

Writing short, independent texts compelled us to make careful choices about what to include, what to simplify, and what to leave open. Working with a limited word count meant accepting that clarity often comes not from saying more, but from saying just enough — and trusting that the reader would continue to think beyond the page.

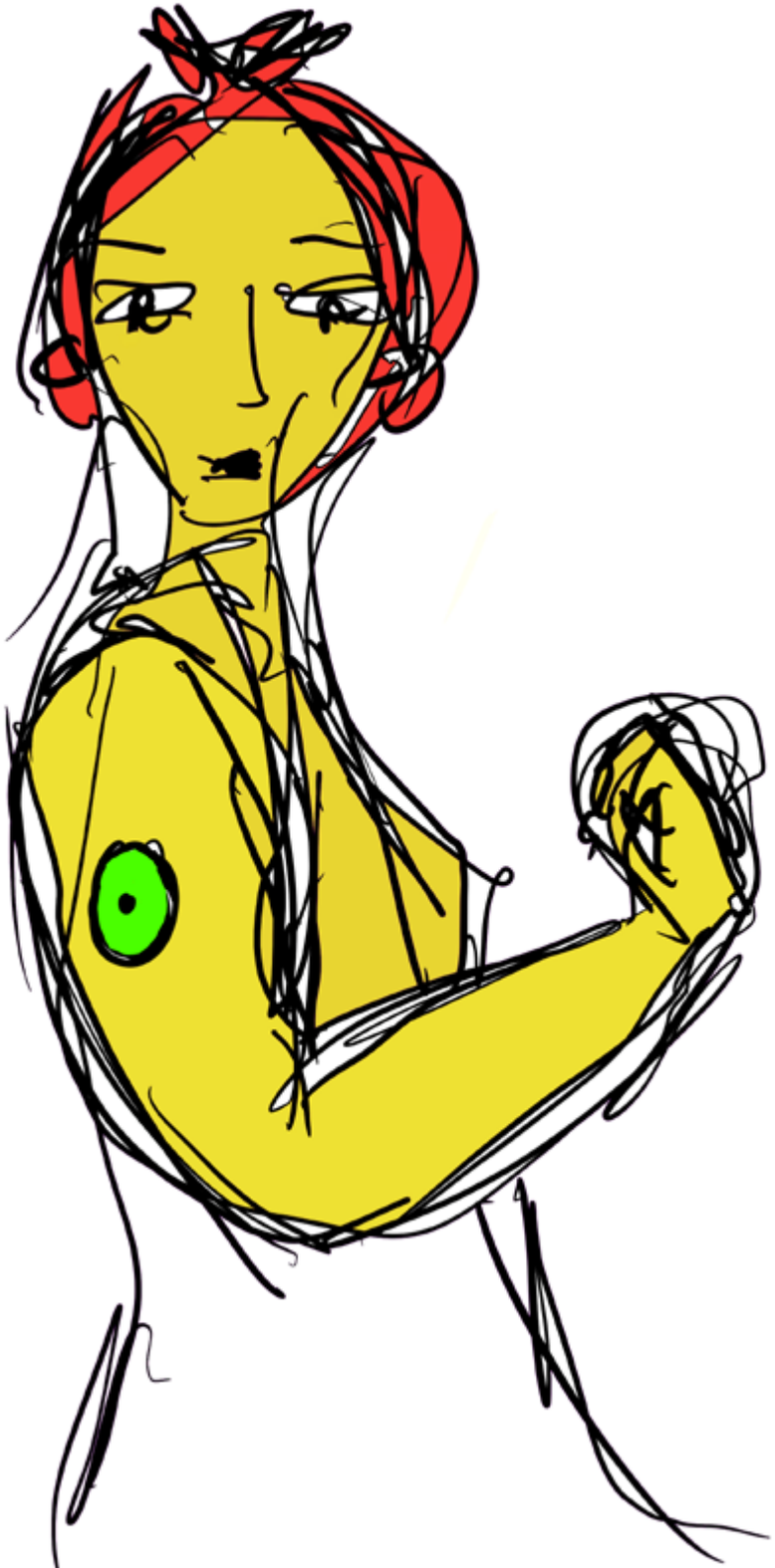
Each text has been written in dialogue with specialists in the field. These exchanges were not only scientific revisions, but also moments of shared learning. Questions about wording, metaphors and emphasis often revealed assumptions on both sides and led us to rethink how scientific knowledge is framed when addressed to non-specialists. In some cases, the act of explaining changed our own understanding of the science and technology we had been working on throughout the years of the project.

An equally important conversation unfolded with the illustrator, Inês Montalvão, and graphic designer, Joana Monteiro. As Inês confides in her note, the illustrations sometimes clarify ideas, sometimes challenge them and sometimes open up new interpretations that the words alone did not anticipate. Decisions about the book's graphic composition were a further part of the process of constructing meaning.

Through this collaborative work, we have abandoned the single, authoritative voice in exchange for the embrace of plurality and uncertainty. We invite readers to see themselves as part of this process, continuing the dialogue through their own readings, questions and reflections. The entries are envisioned as starting points, as springboards for further inquiry. They are anything but fixed or conclusive definitions.

We hope you enjoy this journey as much as we did!

Rita Campos
Kristen Connor
CES, Centre for Social Studies of the University of Coimbra



ILLUSTRATOR'S NOTE

The creative process behind the illustrations for *BIOASSEMBLER* began with a very clear question about creative freedom. I was not interested in making technical drawings, diagrams that explain, or images that obediently translate science into something legible and neat. What I wanted instead was to linger in the uncommon — those spaces where meaning is suggested rather than delivered, where an image can sit beside a text entry without mirroring it, and still resonate. The drawings are not explanations; they are companions.

Each illustration is linked to a text entry, but never as a direct or literal interpretation of its immediate content. I was drawn to what escaped the page: the emotional residue, the overlooked detail, the human (or non-human) presence between lines. I wanted to illustrate the life of someone who lives with a sensor and depends on it to thrive in their day-to-day, so often a woman like myself, without reducing her to data or technology. These lives are complex, messy, and resilient. They are lived at the intersection of biology, devices, care, and adaptation.

This journey took me through simple and unusual things alike: a coffee cup, an organic carrot, a street light on the road of ethics, antibodies, COVID-19 tests, freedom carnations, a knitted sweater, microchips and wafers that are not exactly cookies. From the mundane to the microscopic, from the poetic to the infrastructural. Life is never dull, right? Science, especially when it becomes intimate, rarely is.

My process was slow and porous. I read many of the text entries and began doodling in the empty margins of the page, letting the words flow into my hand. These first drawings were not planned; they emerged almost accidentally, as if thinking could bypass language for a moment. I let them simmer. Later, I returned to the ones that lingered with me: the sketches that made me want to draw them again, to stay with them longer. From there, I developed more intentional sketches, and eventually found myself working on several drawings at once. Some resolved quickly; others resisted closure and had to be revisited repeatedly until they felt complete. This is unusual for me — I often prefer to draw in one sitting — but these images asked for time.

The process felt easier, and richer, because of my background in science. I could return to familiar concepts while encountering many new ones, learning as I went. As a curious mind, this is something I genuinely enjoy. Bioassembler became a perfect combination of nerdiness and creative freedom: reading, researching, questioning, and translating; not into clarity, but into feeling.

This approach is deeply rooted in my focus at the intersection of art and science. Alongside illustration, still a big part of my practice, my work formerly involved mostly science communication and science exhibition design for a long time: spaces where the challenge is not only to inform, but to connect. To make science relatable, tangible, and emotionally resonant. I am interested in how scientific knowledge can be experienced rather than consumed, how it can evoke curiosity, care, discomfort, or wonder.

Ultimately, I hope these illustrations do one of two things: bring a smile, or spark a desire to know more. To look deeply at fierce women like Henrietta Lacks, whose cells also changed the course of medical history, or at your "random" type 1 diabetic friend, quietly navigating a world of sensors and signals, also a kind of superhero. These drawings are an invitation to notice, to feel, and to stay curious.

Inês Montalvão

A first glimpse: why this book?

Every research project begins with questions. What if we could integrate bio-inspired assembly into semiconductor manufacturing, and create a new generation of biosensors? How could such innovations transform the production of silicon-based, label-free multiplex biosensors? And what role could they play in addressing pressing current social and economic challenges, from health and food security to climate change and natural resource conservation?

These were questions that inspired the BIOASSEMBLER project.

Now, you might be thinking: *Biosensors? What exactly are those?*

The truth is, you probably already use them or at least have seen them. Think of glucose monitors, COVID-19 rapid tests, pregnancy tests. You may not have called them "biosensors," but many of us have relied on them for important information about health and life.

Introducing a biosensor

A biosensor is a tool to detect different substances using a biological component — it is a "biological sensor". And we don't need to go far to understand what a sensor is or does. Our nose and tongue are equipped with nerve cells that act as sensors. When we bite into a lemon, we can taste the sourness on our tongue and detect the characteristic lemony smell generated by compounds such as limonene, linalool and citral.

Just as we humans can detect odours and flavours, sensors respond to stimuli, such as heat, light or pressure, and generate signals that can be measured and interpreted. Biosensors work in a similar way. These devices can detect a wide range of substances, such as proteins, pathogens and toxins, from samples such as blood, saliva or water.

A biosensor is made of two main components: a biological element, also called a bioreceptor, such as an enzyme or antibody; and a transducer, an electronic device that changes one form of energy into another. A microphone is one type of transducer. It transforms sound waves into electrical signals. This electrical current can then be amplified, raising the volume of the sound. When it comes to biosensors, transducers convert biological events into electrical signals which can be interpreted by a person or a computer. The bioreceptor recognizes and interacts with the substance to be detected, called a target analyte. This interaction is a biological event, which can take the form of a shift in brightness of the biological element or a change in mass. This generates a signal that the transducer converts into a measurable output.

Let's look at a classic case: a biosensor used for monitoring glucose levels.

In this context, the bioreceptor (an enzyme) interacts with glucose (the target analyte) in a sample of blood. This reaction produces an electrochemical signal that can be measured, interpreted and acted upon. While most glucose-monitoring biosensors are electrochemical, there are other types of

biosensors, each with advantages and limitations that depend on the target analyte, the application, and the context in which it might be used.

Looking ahead, biosensors offer significant possibilities across many fields. In healthcare, they enable rapid diagnostics, continuous monitoring of chronic conditions, and personalized medicine, often outside of traditional clinical settings. In environmental monitoring and food safety, biosensors can provide early detection of contaminants, pathogens or pollutants, helping to prevent outbreaks and reduce environmental damage. Advances in materials science, nanotechnology and data processing are also expanding the sensitivity, speed and portability of biosensors, making them increasingly accessible and versatile.

Despite these opportunities, important challenges remain in both the use and manufacturing of biosensors. Ensuring long-term stability, accuracy and selectivity of the biological components can be difficult, especially when devices are used in complex real-world samples. Manufacturing biosensors at a large scale while maintaining consistent quality and keeping costs low is another major challenge, particularly because biological elements can be sensitive to temperature, humidity and storage conditions. Addressing these limitations is essential for translating laboratory prototypes into reliable, widely used technologies.

Introducing the BIOASSEMBLER project

The BIOASSEMBLER project proposed to expand the possibilities for these familiar gadgets and to overcome some of the challenges in their production. In simple terms, its goal was to develop a new way of manufacturing biosensors that can detect multiple biological molecules at the same time. This is known as *multiplex* biosensing, and it opens the door to far more powerful and informative sensors than those commonly available today.

To understand why BIOASSEMBLER matters, it helps to look at the sensors we already rely on. Many everyday technologies use tiny devices called MEMS (Micro-Electro-Mechanical Systems). These sensors allow our smartphone screen to automatically re-orient themselves or the car airbags to deploy at the right moment. MEMS devices are built on silicon wafers using extremely precise and expensive manufacturing processes that take place in ultra-clean environments and require highly skilled specialists. This model works very well for traditional sensors, but it becomes a major obstacle when we try to combine MEMS technology with biology.

Biosensors have enormous potential. And if these tiny devices could detect several biological markers at once, their value would increase dramatically. However, turning this vision into reality is not straightforward. The key difficulty lies in integrating delicate biological molecules onto extremely small silicon sensor elements. These elements are often only a fraction of a millimetre wide, making precise placement incredibly challenging.

The problem becomes even more complex when different biomolecules must be positioned side by side without mixing, and when this process must be repeated thousands or even millions of times to enable mass production at an affordable cost. Existing approaches struggle at this scale and level of precision, and can damage sensitive biomolecules in the process.

This is where BIOASSEMBLER introduces a new approach.

The project combined two advanced fields: photolithographic chemistry and nanobiotechnology. It developed *bio-intelligent* manufacturing technologies that allow biomolecules to be placed precisely onto wafers using a fast, scalable, and smart process - something that had not been possible until now. The ambition was not only to create a new generation of biosensors, but also to transform semiconductor manufacturing, strengthen European leadership in bioelectronics, and open up new opportunities for research, business, and work.

But BIOASSEMBLER was never only about technology. The project was born out of a dialogue that connects biology and electronics, science and society, research and art. And so, it also explored social, ethical, and environmental questions. Researchers from very different disciplinary areas, such as engineering, natural sciences, social sciences and humanities, worked together to ask: who benefits from these devices? How will they affect everyday life, policy, and industry? What responsibilities come with new technologies?

Now… why this book?

This book grew out of a shared conviction: science does not exist apart from society. It connects with people not only through data and results, but through trust, transparency, and shared values. How science is communicated shapes how knowledge is understood, questioned, and valued: who is invited into the conversation, and how are those invitations made? This publication emerges out of a spirit of collaboration and engagement.

The book presents 50 short illustrated entries — each no longer than 500 words — that can be read independently and in any order. Rather than following a single linear narrative, each text offers a concise snapshot on the project's ideas, challenges, and/or reflections, allowing the reading to follow the reader's own interests and curiosity. Throughout the text, you will come across words in bold – these indicate topics that are covered in a separate entry. If you found that the text above, which describes the BIOASSEMBLER project, contained many unfamiliar words, you might be pleased to know that you can find a simplified explanation for each of them in these entries.

The topics of these entries were not defined in isolation. They emerged through a *social dialogue*: an ongoing exchange between team members from different disciplines, external institutions, and citizens, including teenagers and young adults. Their questions, concerns, and perspectives played a central role in shaping the content of the book, helping ensure that it reflects not only scientific priorities but also social relevance and lived experience.

This participatory approach also guided the choice of the book's title, through a consultation in which participants selected the option they found most appealing — the title that would make them want to actually read the book.

All texts were scientifically reviewed to guarantee accuracy, while remaining accessible to non-specialists. Alongside the technical aspects of biosensor development, the book explores broader social, ethical, and environmental dimensions of biotechnology. To support this modular and flexible reading experience, key concepts are highlighted and addressed as stand-alone texts, and the content is organised into four sections that follow a journey of discovery, from an introduction to biosensors to their real-world applications and the wider implications of biotechnology innovation.

At the heart of this approach is the belief that providing more facts alone is not enough to build trust in science. Meaningful engagement also depends on emotional connection, cultural context, and the feeling of being included rather than instructed. For this reason, collaboration between science and art is not treated here as an add-on, but as a central element of communication.

The illustrations by Inês Montalvão and the graphic design by Joana Monteiro play a crucial role in this process. Rather than functioning as scientific diagrams, the illustrations offer imaginative interpretations of scientific ideas. Together with the graphic composition of text and image, they create visual narratives that make complex concepts more approachable, engaging, and memorable.

By using an art-based approach, the book reaches beyond readers who already feel comfortable with scientific topics, inviting in those who might not initially consider themselves interested in biosensors or biotechnology. At the same time, the visual interpretations are intended to provoke and challenge readers who are already familiar with the subject and experts, encouraging them to see well-known concepts from unexpected angles and to reflect on their work in new ways.

Texts and illustrations come together as an *assemblage*: a convergence of ideas, disciplines, voices, and viewpoints that mirrors the collaborative nature of the BIOASSEMBLER project itself. This notion of assemblage also connects to the performance *BioAssemblage*, created during the BIOASSEMBLER artistic residency by contemporary artist Andrea Inocêncio, which made visible the hidden rhythms of laboratory work and invited audiences to experience the interplay between biomolecules, sensors, and human creativity.

Beyond documenting the project, the book has a broader educational ambition. Designed with schools, universities and learners of different ages in mind, its short, stand-alone texts and visual storytelling aim to spark curiosity, encourage reflection, and invite critical thinking about the role of science and technology in society. It reflects a view of communication as a participatory process, one in which scientists and citizens alike contribute to shaping understanding and meaning.

A final invitation remains: to continue this conversation by exploring the BIOASSEMBLER comic book, *An illustrated journey through scientific discovery — the BIOASSEMBLER project*. Illustrated by André Caetano, this comic offers a behind-the-scenes view of scientific research as a collaborative, imaginative, and human endeavour.

Rita Campos
BIOASSEMBLER Communication Coordinator

SCIENTIFIC REVISION

The scientific accuracy of the texts is due to the rigorous and dedicated revision of the texts by members from the BIOASSEMBLER project and the project ethics consultant.
In alphabetical order, they are:
Anna Spehar
Bernardo Valente
Emilia Barannik
Esther Wenzel
Filipe Santos
Gisela Ibañez
Hugo Pinto
Jan Terbrack
Joana Sousa
Joel Janhonen
Laila Al-Halabi-Frenzel
Mathias Reisbeck
Petri Saviranta

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We are very grateful to all the people who took some time to share with us their knowledge, experience, perspectives and doubts about biosensors, through online or in-person interviews, structured conversations (*focus groups*) or informal dialogues, helping to identify topics that can be of interest to a broader audience.
We would also like to thank the young people who helped choose the title of the book.
A special thank you to former BIOASSEMBLER member Bianca Brito, who drafted the first entries of the book and helped guide the conversation with the students.

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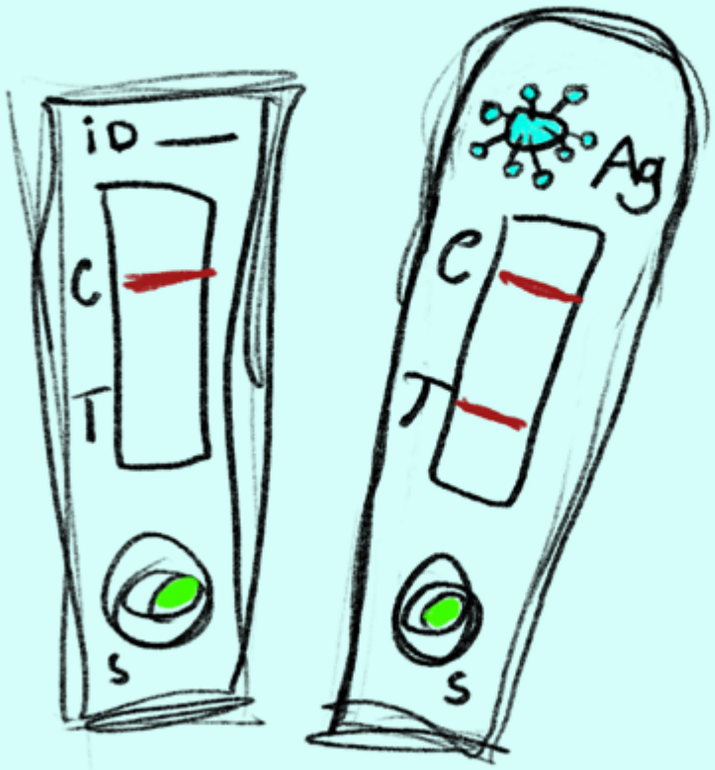
1. Overview

THE ESSENTIAL PRIMER



BIOSENSING IS ALL AROUND US

We expect to buy food free of contaminants and harmful pathogens.

We need to be sure that the water we consume has been tested for pollutants.

We want to regularly track the impact of our physical training on our bodies.

Biosensing technologies exist and are being refined for each of these needs and wants.

As tools to detect substances such as proteins, pathogens and toxins, biosensors are used in a wide range of fields: medical diagnostics, **food** safety, agriculture, **environmental monitoring**, **forensics** and more. They are also being developed for the real-time or continuous monitoring of disease **biomarkers**, with the goal of enabling early diagnoses and personalized medical treatments.

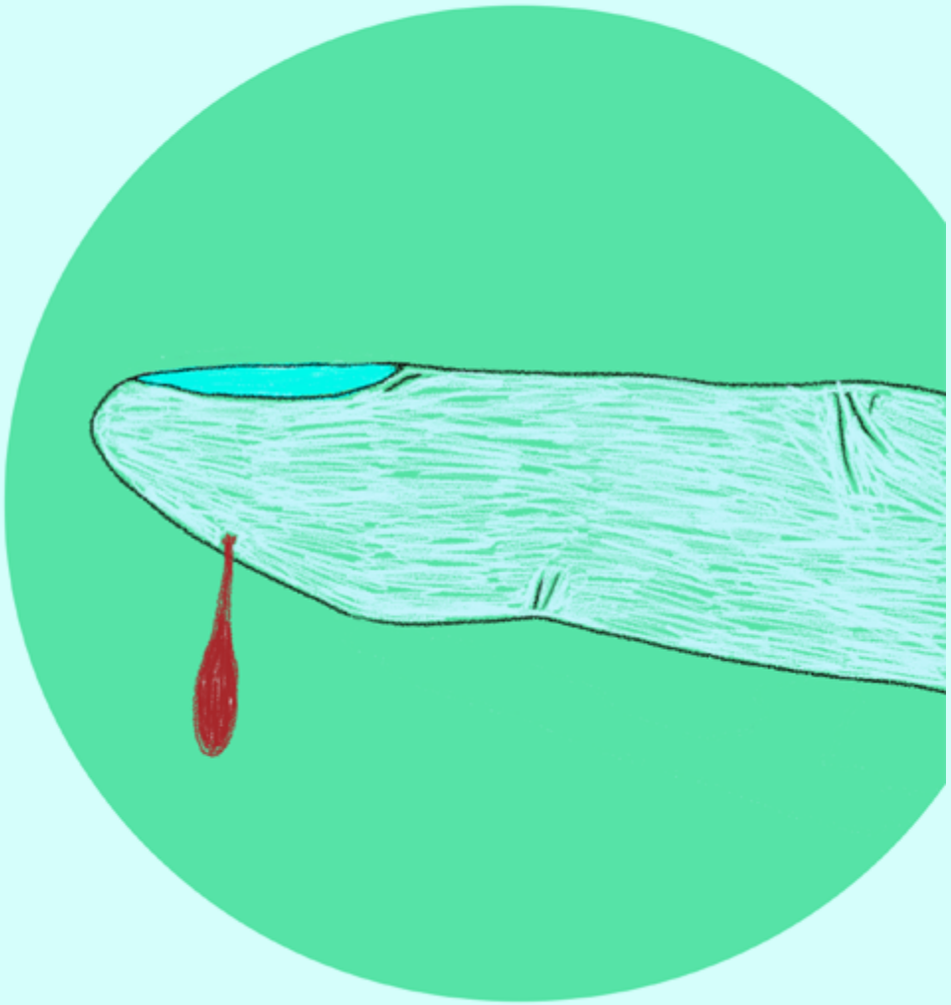
Biosensors are widely used and increasingly innovated because their detection methods are quick, accurate and cost-effective.

However, to accurately detect substances in complex biological samples, biosensors must be highly sensitive, shelf-stable and built under very specific conditions.

Patients, users, scientists and technicians rely on the performance of biosensors to carry out ordinary activities and for diagnoses that can deeply impact our lives. If you've ever sat staring at a pregnancy test praying for one strip (or two), you know what we mean. Yeah, the more precision the better.

Researchers have been working continuously to improve biosensors, developing new materials, coatings and detection methods. Within the wider world of **biotechnology**, biosensing is an exciting, multi-disciplinary area of research and innovation. As more and more biosensors reach the market, it is important that we understand how they work, their advantages and their limitations.

The more biosensors evolve, the more uses can emerge. Can you think of any other areas that might benefit from biosensors? Can you imagine any risks, negative impacts or social and political concerns that biosensors might raise?



ORIGINS OF BIOSENSORS

Biosensors have been around for quite some time. The first known example was the enzyme electrode created in 1962 by the American biochemist Leland Clark, an important figure in biosensing.

To tell this story we must go back to 1956, when Clark designed a platinum electrode to measure oxygen reduction in a solution and determine blood oxygenation.

An electrode acts as a conductor that transfers or collects electrons. In Clark's device, the platinum electrode facilitated a chemical reaction in which oxygen molecules gained electrons, becoming reduced and converted into water. By observing the resulting flow of electrons, Clark could measure the extent of oxygen reduction and indirectly determine the oxygen concentration.

However, this instrument was not yet a true biosensor, as it lacked a biological component.

Several years later, Clark added such a component: an enzyme called glucose oxidase. Enzymes are substances produced by living organisms that act as catalysts, converting one substance into another.

With the addition of the enzyme, the oxygen sensor could now indirectly measure glucose levels in a **sample**. The improved device, introduced in 1962, became known as the "enzyme electrode".

And so, the first device capable of rapidly measuring blood glucose was born! This invention marked a turning point in medical diagnostics, paving the way for modern glucose monitoring and many other biosensing technologies used in healthcare today.

Since then, biosensors have come a long way. Researchers have incorporated other biological elements such as **antibodies** and use new materials and innovative production methods. Today, biosensors can detect a vast range of substances and play an important role in medicine, research and everyday **health** monitoring.

QUANTIFICATION

Quantification, at first blush, is straightforward: it is the measurement of something expressed in numbers. Some things lend themselves to quantification easily: how many apples are in your bag? Is your suitcase under 23kg?

By contrast, many phenomena central to the human experience are not so easily quantified, including perceptions of pain, extreme heat, happiness or even the weather. People have developed countless tools to quantify such experiences with varying success.

Ever been asked to rate a customer service call out of 5 stars? At your last doctor's visit, did you rank your pain on a scale of 0 to 10? Or maybe you've read the *World Happiness Report*, ranking countries by life evaluations and emotions. These examples of quantification aim to guide improvements to services, treatments or even the quality of life, however they can only partially capture the experience in question.

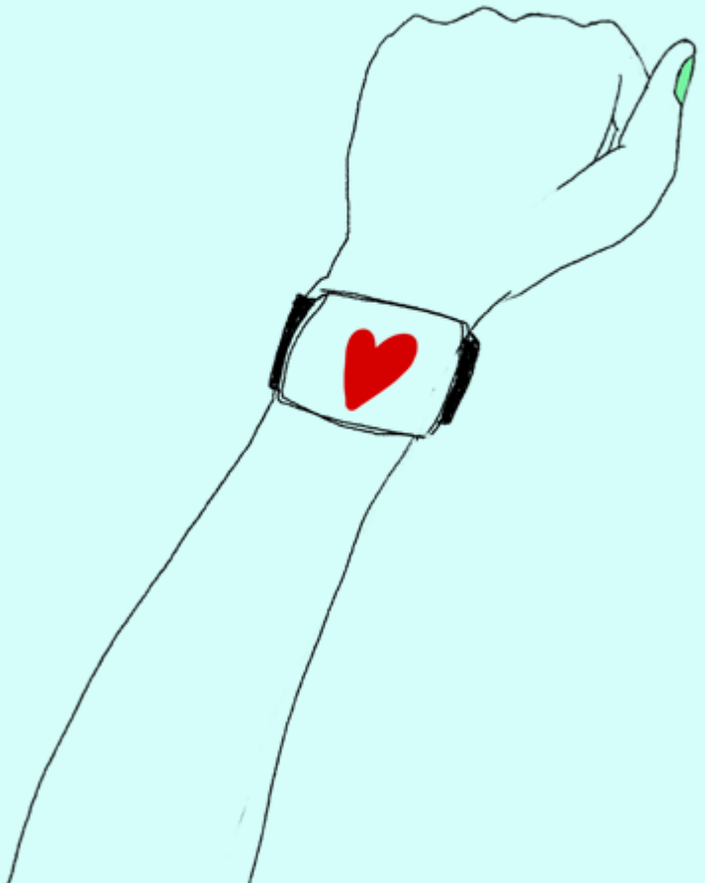
Quantification is incredibly commonplace in the 21st century, in part due to smartphones and other tracking devices that proliferate in our daily lives. Biosensors are one such tool that offers novel ways to quantify **biomarkers** in humans and other organisms. And even in the environment, tracking pollutants or toxins that might be present in the water, soil or air.

Consider lactate, a by-product of human metabolism that the liver removes from the blood. Elite athletes, coaches and sports medicine researchers are increasingly interested in lactate as a signal of muscle fatigue. Using lactate biosensors, it is now possible to measure blood lactate levels continuously, providing insights into how the body responds to exercise in real-time. But this raises questions: how much lactate is too much, over what period and under what conditions? Establishing safe and meaningful thresholds for biomarkers like lactate is a long process, requiring experiments, evidence and consensus-building.

This kind of quantification has benefits. For example, coaches might use lactate data to design individualized training programs for athletes. You might have seen high-performance athletes with wearable biosensors to monitor their performance.

Similarly, wearable biosensors are becoming widely used for personal health monitoring. These devices track vital signs and detect changes in glucose, heart rate, and body temperature, helping individuals manage their health and prevent medical issues in real time, anytime and anywhere. At the same time, continuous self-measurement carries risks, including psychological ones.

How does quantification and self-measurement shape the way you understand and navigate your own experiences, from tracking health or fitness to evaluating emotions or making decisions? What are some of the benefits and limitations of these practices?



MEMS SENSORS

Micro-electro-mechanical sensors (MEMS) are our daily companions, hidden from view inside many electronic devices. From smartphones to cars, fitness trackers to smartwatches and countless "Internet of Things" (IoT) devices, MEMS sensors work behind the scenes to make these technologies possible. They are small but essential components in the technology we use every day. Without them, many devices and systems we rely on would not function as they do.

These tiny sensors, smaller than a single strand of hair, detect even the slightest changes in their surroundings. They convert mechanical, thermal, and other variations of energy into electrical signals. This enables devices to respond to motion, pressure, temperature, sound and more. MEMS sensors continuously feed data to control systems, which use this information to take appropriate actions.

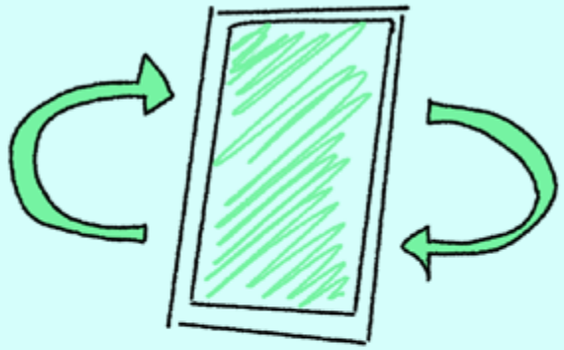
For example, in new cars, MEMS sensors monitor tyre pressure, air quality, acceleration, rotation and other important factors. In vehicles with advanced driver-assistance systems (ADAS), they are essential for safety and automation. Similarly, wearable devices rely on MEMS sensors to track physical activity, like how fast you're running or the angle of your movements.

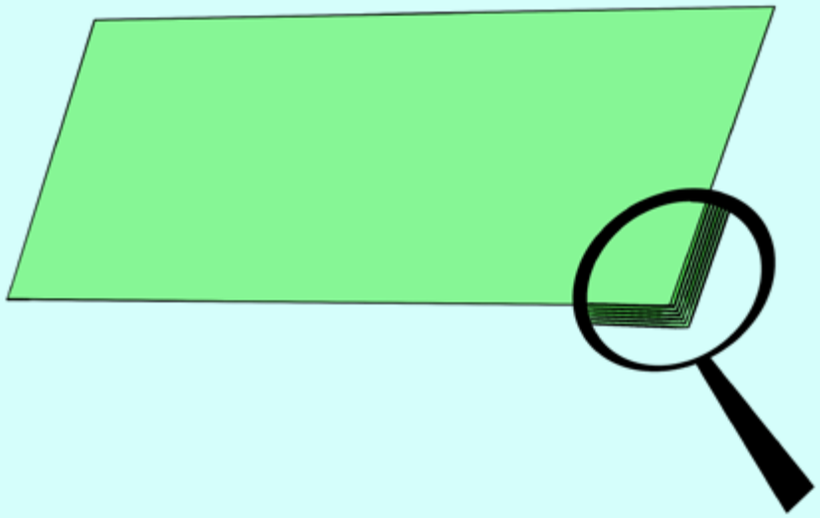
Don't drive? No wearable tech? You're likely familiar with devices that contain some of these other MEMS sensors, as they are found in many everyday devices, helping them function in smart and precise ways.

Accelerometers detect motion and speed changes, enabling features like airbag deployment and screen rotation in smartphones. Gyroscopes measure rotation, making them essential for gaming controllers and drone stability. Pressure sensors monitor air or fluid pressure, ensuring safety in tyre pressure monitoring systems and accuracy in weather instruments. Temperature sensors help regulate thermostats and refrigerators, and wearable devices. Microphones convert sound into electrical signals, allowing smartphones and hearing aids to capture audio. Chemical sensors detect gases and chemicals, improving air quality monitoring. Optical micromirrors manipulate light, playing a key role in projectors and medical imaging. Magnetic sensors measure magnetic fields, providing direction in compasses and enhancing safety in anti-lock braking systems. Finally, inertial measurement units (IMUs) combine multiple sensors to track motion and orientation, making them essential for Virtual Reality (VR) headsets and fitness trackers.

But how are they made? MEMS sensors are etched onto silicon **wafers** in highly specialized **clean rooms** using techniques similar to those used for making microchips. Given the high diversity of applications, each type of sensor requires precise tools and processes, making their production complex and specialized yet cost-effective. Due to the small size of a single sensor, many sensors can be manufactured from a single silicon wafer.

These sensors are so important that they're now being explored for biosensing applications, such as real-time health monitoring. Often called **bioMEMS**, these tiny sensors are able to analyse small droplets of saliva, blood or urine, acting as miniature diagnostic labs for personal and medical use.





MEMS BIOSENSORS (OR BIOMEMS)

MEMS biosensors, also known as bioMEMS, are tiny devices that combine micro-electro-mechanical sensors with biological elements, like antibodies, to create tools that can detect specific biological markers. Scientists are still experimenting with this technology to make the most of its potential.

One project that aimed to advance this field was the Horizon Europe-funded **consortium** BIOASSEMBLER. This team of international researchers worked on new ways to make MEMS biosensors a reality! And they wanted to go even further, and develop a *multiplex* biosensor, capable of simultaneously detecting several biomarkers.

But what makes this so challenging?

First, MEMS sensors are incredibly small. They're about as thin as a sheet of paper, or about 100-200 micrometres thick. Manufacturing at this scale requires highly precise machines and powerful microscopes.

Second, placing **antibodies on biosensors** is tricky. These biological elements need to stay exactly where they are placed on the tiny sensor elements. If they spread to the wrong area or interact with unintended elements, the biosensor won't work properly. Since a single silicon **wafer** can hold thousands of chips with tens of thousands of individual sensors, precision is critical.

Third, the biosensors must work consistently. For them to be commercially viable, their performance must be reliable and identical across every batch. Achieving this level of reproducibility is a tough challenge.

Finally, the manufacturing process is expensive. Over the years, silicon wafers have become larger and microchips have become smaller, allowing thousands of chips to fit on a single 30 cm wafer. High chip density is necessary to keep costs low, but it also adds complexity to the manufacturing process.

One possible solution for placing antibodies on MEMS sensors is DNA printing, called **photolithographic DNA synthesis**. While large inkjet printers are already used to create OLED TV screens, printing biological molecules like antibodies is much harder. These molecules have unique requirements and there isn't a universal "ink" that works for all situations.

Researchers are still working on ways to overcome these challenges. If successful, multiplex MEMS biosensors could open up new possibilities for health and environmental monitoring, diagnostics and more!

BIOTECHNOLOGY

Despite being a well-known term, biotechnology evades easy definition. It can be explained as the use of living systems or biological molecules to develop new technologies. Most often it is associated with genetic engineering, genetically-modified organisms (GMO) such as crops and novel drugs. Synthetic insulin and mRNA vaccines (like some of the COVID-19 vaccines) are two notable examples of commonplace biotechnology products.

From the 1970s through to the 1980s, biotechnology was largely synonymous with **recombinant DNA technology**. This changed over the course of the 1990s and early 2000s as new developments in stem cell research, highly-publicized international research projects such as The Human Genome Project (1990-2003) and the cloning of the good sheep Dolly (1997), broadened ideas and public debate around the definitions and ethics of biotechnology**.** An expanded definition of biotechnology, then, is the use of living organisms (cells, bacteria, fungi, etc.) to create or modify products or technologies. This includes cutting-edge CRISPR gene editing technology, as well as ancient technologies such as fermentation - *cin cin! Saúde!*

Considering biosensor innovation, the BIOASSEMBLER project proposed to apply biotechnology at the nanoscale to revolutionize how computer chips are made, combining nanobiotechnology with photolithographic chemistry, a method already used in chip manufacturing. It explored the synergies between nanotechnology and biotechnology in production methods, namely combining biotechnology with MEMS sensors in a novel bio-inspired self-assembly process. Through this innovation, it may be possible to deposit dozens of different biomolecules simultaneously onto thousands of exact, predetermined positions on a silicon wafer!

Altogether, the fusion of biotechnology and nanotechnology opens new paths towards innovative, sustainable production technologies. This can potentially reshape the semiconductor industry, reinforce European leadership in innovation and generate new business and job opportunities.

Today, biotechnology is a huge, multidisciplinary and global industry. It is made up of people of all stripes: engineers, biologists, biochemists, computer scientists, technicians, lawyers, business and sales-people, science communicators, bioethicists and many, many more.

But that's not all. Unlike straightforward terms like **clean room**, others like **bioethics** and biotechnology are complex, contested and plural. This means that they can have more than one definition or meaning depending on who's doing the defining. For more, check out **a critical lens on biotechnology.**

A CRITICAL LENS ON BIOTECHNOLOGY

Pssst, go back and check out the entry on **biotechnology** first, if you haven't already!

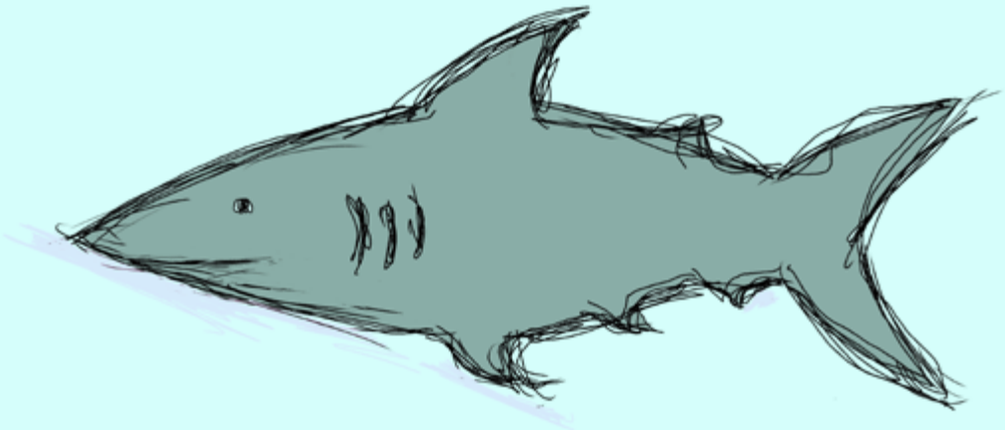
Definitions and understandings of biotechnology change depending on who you ask. One group of people who have spent decades trying to understand biotechnology and what's unique about it have been interdisciplinary scholars of Science, Technology, and Society - also known as STS.

To understand biotechnology, these scholars have drawn on theories such as biopower, put forward by historian and philosopher Michel Foucault in 1976. Biopower is a form of political power that seeks to control populations through the management and control of biology, including reproduction, health and death. Some STS scholars have argued that what is unique about biotechnology is not just the technology (such as recombinant DNA technology) but also the commercial relations between scientists and industrialists, the race to patent new technologies and above all the engineering priority to enhance control over the human body and other forms of life.

More recently, critical* scholars have proposed the term biocapitalism to refer to an economic system built on commodifying life (treating biology, including human bodies, as sources of profit) and on creating new products from existing forms of life. Framed in this way, biotechnology is the outcome of biocapitalism. It is not a single technology, but a set of commercial or economic relations that are organized around developing ways that DNA, stem cells, antibodies, blood and so on, can be made profitable or incorporated into new technologies that are economically valuable. While biotechnologists often frame their products as beneficial (and indeed, many have been, just take the mRNA COVID-19 vaccines), these commercial relations, new technologies and patented or proprietary products produce new challenges and inequalities. For example, industrial agricultural corporations' patenting of GMO seeds has created serious problems for smallholder farmers around the world, including financial and legal burdens for growing (or being accused of growing) such controlled crops.

While it has become normalized that public universities should have a close relationship with industry partners, this paradigm emerged in the late 1970s alongside advancements in biotechnology and today dominates what is often naturalized as the "research and innovation landscape". Goals of this relationship are often to co-create knowledge, increase collaboration and build dynamic institutions that have social impact. Yet, driven by commercial interests, these priorities raise questions about the role of fundamental (or basic) research and public universities in society; public access to knowledge and technology; and the relationship between public funding and private corporations.

*The *critical* in critical scholarship is often misunderstood as meaning to disapprove or point out faults. In the context of critical studies, it means to analyse power relations and their impact on the production of knowledge and society. These in turn shape the relations between people, some of whom wield great power and others who are exploited, marginalized, or oppressed. The goal of critical scholarship is to understand society (which is always changing) in order to transform the status quo through collective action.



BIO-INSPIRED TECHNOLOGY

In simple terms, bio-inspired technology refers to innovations that draw ideas from biology. It's closely related to biomimicry or biomimetics, which involve learning from nature's successful forms, structures, processes, strategies and efficiency to design and build new technologies. While biomimicry focuses more on imitating or replicating biological mechanisms for technical applications, bio-inspired approaches apply nature's principles to design new technologies without directly imitating them.

Let's check out a couple of examples:

— DNA has a natural propensity to form double-stranded structures between complementary, single-stranded sequences. Technology based on this principle, such as a biosensor that uses **synthetic DNA guided assembly** to detect target **analytes**, is a bio-inspired technology.

— Sharks are covered in special scales called dermal denticles ("skin teeth"). Their microstructure, patterns and properties provide hydrodynamic benefits and protect against parasitic organisms. Super-clean skin helps sharks swim super-fast and prevents algae and barnacles from hitching a ride (unlike crusty whales and sea turtles). The creation of biomimetic surfaces modelled on dermal denticles can help in the development of more aerodynamic planes, faster swimsuits, ship hulls that remain free from barnacles and even anti-microbial surfaces for use in hospitals!

— Butterflies have incredible wings covered in micro-scales that are hydrophobic (repel water) and resist fogging. These features help the wings stay clean. Researchers are exploring how to mimic these nanostructures on glass to create "self-cleaning glass" that remains clear, fog-free and dirt-resistant.

Bio-inspired design and biomimicry are especially prominent concepts in nano- and micro-engineering, industrial design and architecture. Yet, the development of technology based on the observation of nature is nothing new. From umbrellas to velco (that childhood friend), countless technologies, building structures and everyday items have been "bio-inspired."

While biomimetics and bio-inspired technology offer compelling innovations, there are some precautions and perspectives to consider. As with other manufacturing processes, the enthusiasm or even the race to develop new biomimetic and bio-inspired technologies and products need to be coupled with efforts to protect the very life that is the source of inspiration. There are currently tens of shark species that are vulnerable, endangered or critically endangered. What is a world with shark-like surfaces but few sharks?

BIO-INTELLIGENT MANUFACTURING

Bio-intelligent manufacturing, also known as BIM, is a new term that is being used among production scientists, biotechnologists and nano-biotechnologists to describe a transformation in industrial manufacturing methods and products. It is a neologism: a newly coined word whose longevity is still to be decided – by the public, by you!

Industrial manufacturing is the large-scale production of goods, including furniture, toys and parts or materials that go into other products. As a result of the industrial revolution in the late 18th and 19th centuries, industrial manufacturing replaced small-scale artisanal production. That sweater your grandma knitted for you? That's artisanal production. And if she spun the yarn herself (ideally from her own flock of sheep), that would be artisanal production at its finest.

Historians and technologists mark phases of the industrial revolution according to eras in which new technologies and fuel-sources dominated. For example, the first industrial revolution (~1760 to 1840) was powered by steam. And the second (~1870s to World War I) was driven by railroads, steel and telegraphs. What came after is harder to pin down, but the key point is that manufacturing keeps changing. New terms for large-scale changes in production help highlight what has changed, and ideally why those changes are important.

Here are some of the contenders for the third (or fourth? or fifth?) phases of the industrial revolution:

— A heavy hitter, fighting for the title of Third Industrial Revolution is *The Information Age* or *Digital Age*. Born in 1947 at the same time as the transistor (a small but mighty electronic switch), this champ stands out for having revolutionized communications, information storage and none other than the Internet itself.

— Hoping for a knockout to claim the prized title is the lightweight Industry 4.0, also known as 4IR, short for Fourth Industrial Revolution. A 21st century cyborg with a quick step, 4IR brings advanced robotics and artificial intelligence into automated, connected global manufacturing and supply systems.

— And last, a novice with a promise, our very own Bio-Intelligent Manufacturing! BIM hopes to unseat Industry 4.0 by integrating biological processes, organisms and materials and knowledge from biology to increase the efficiency of industrial manufacturing, including promoting **sustainability** and circularity in production. The brainchild of technical, digital and biological processes (such as CRISPR gene editing), BIM models itself on nature and dreams of transforming production so that it can stay within planetary boundaries and use limited resources (bio)intelligently. BIM doesn't always use biological components, but can also simply be inspired by biology, or **bio-inspired**.

The truth is, rather than rivals, these terms represent different ways of thinking about ongoing transformations in industrial manufacturing.

The BIOASSEMBLER consortium is an example of an innovative bio-intelligent manufacturing project, as it developed a bio-inspired method to assemble biosensors on silicon wafers, with the goal of producing many MEMS biosensors quickly and efficiently. Techniques used in the project including **biofunctionalization**, **photolithographic DNA synthesis** and **synthetic DNA-guided self-assembly** are all concrete examples of bio-intelligent manufacturing!

2. Core components

BUILDING A BIOSENSOR

SAMPLE

A sample is what you get when you go to the ice cream shop and irritate the server (and the people behind you) by asking to taste too many flavours before buying. Be bold, be experimental, ask yourself: do you really need that lick?

Okay, okay, you might disagree, but the principle is on point: a sample is a small part or quantity of something, whose analysis is intended to show what the whole or larger part is like.

In statistics, a sample is a subset of something (let's say, people), whose study and analysis are then (ideally) representative of a larger subset (for example, of people from a country or region).

In biology, a sample is a material, collected from an organism or the environment for research or diagnostic purposes. If you've ever had to get a blood test done at the doctor's office, that vial of blood extracted from your arm is a sample. When doctors analyse the sample for **biomarkers** or specific **analytes**, they learn a little bit more about your health status.

Samples are critical in medicine, research and drug development. Researchers study samples of blood, urine, saliva, tissue, cells, DNA and much more, to develop biomarkers, understand (and diagnose) disease, test new drugs and tailor treatments for patients.

Also like ice cream, biological samples must be stored carefully because they are subject to degradation and contamination. Labs have clear protocols concerning labelling, sealing, refrigeration and more to ensure that the samples they are working with are in a good condition. This is essential to make sure that the analysis can be reproduced, meaning to always get the same results if the exact same procedures are followed.

Technical questions aside, there are also ethical dimensions to the collection, storage and use of biological samples in scientific research. For more on this, you can see **ethics**, **bioethics** and **cell lines.**

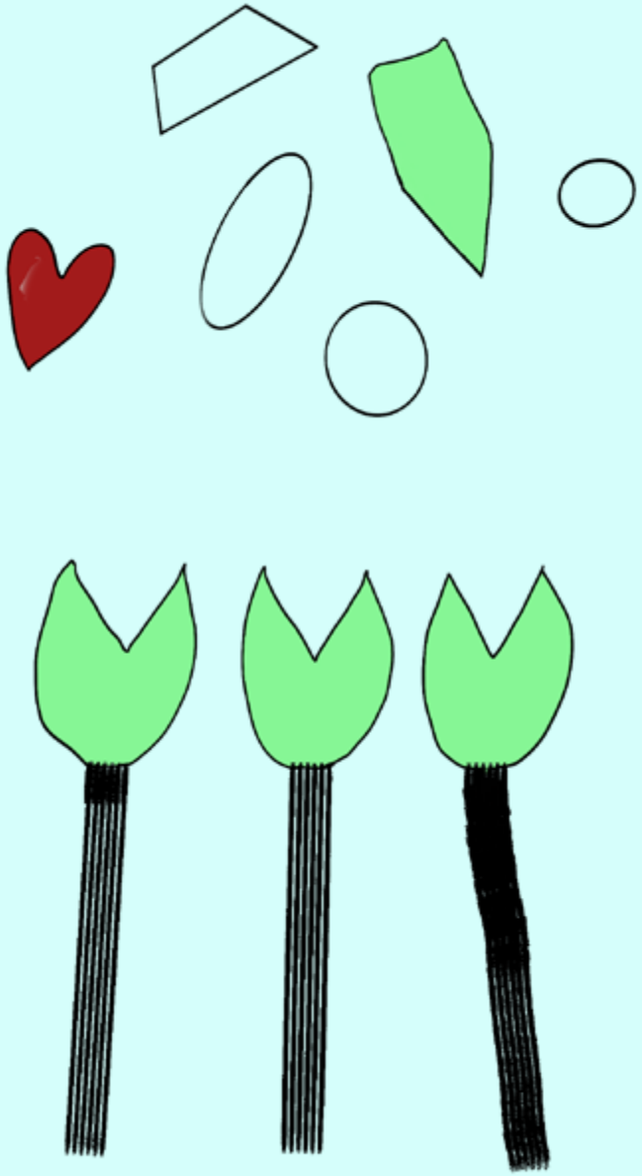
So, what's new with samples and sampling?

Glad you asked. Well, the way doctors and researchers collect vials of blood samples is old school and not that efficient. It requires large volumes of blood (uncomfortable for the patient), cold storage, a lot of labelling and complex transport logistics. All of this adds costs, increases fuel use and can raise ethical concerns.

That's why many researchers are turning to microsampling, which reduces the amount of sample volume needed, cuts down on harsh solvents and reagents and minimizes storage and resource demands. These approaches are helping make research more efficient, ethical and sustainable.

One way to do this is with **microfluidics** (integrated into biosensors and other **lab-on-a-chip** devices), which dramatically reduces the amount of a biological sample required for analysis. Rather than a whole vial of blood, such a device might require only a microlitre or nanolitre of blood.

Microsampling: proof that even a drop of blood can B positive.



ANALYTE

An analyte is a chemical entity — a substance or molecule — that is being analysed, measured or tested. They can range from simple ions and compounds to complex molecules, such as proteins, DNA or RNA.

For example, glucose is the target analyte in Continuous Glucose Monitors (CGM), one of the most widely used health biosensors. Lactate (also known as lactic acid) is the analyte measured by sweat biosensors for athletic performance, which are increasingly popular among athletes. Pregnancy tests, meanwhile, detect the hormone human chorionic gonadotropin (hGC), an analyte present in urine when a person is pregnant.

Analytes are detected by bioreceptors, which can be enzymes, antibodies, or microorganisms. It's like a game of tag, where the bioreceptors are "IT" and they're out to catch the analytes. Except for the fact that any given bioreceptor can only catch the analytes they pair well with. Ahhh a match made in heaven… As Sam Cooke once said, "Cupid, draw back your bow."

While many biosensors are designed and built to detect a single analyte, scientists and engineers are interested in creating multiplex biosensors — biosensors that can detect multiple analytes from a single sample. These kinds of biosensors are more complicated to make, but hey, that's what **consortia** are for.

For instance, the new assembly technology developed within the BIOASSEMBLER project enables the simultaneous detection of two analytes involved in the inflammatory response: C-reactive protein (CRP) and serum amyloid A (SAA). As these analytes are **biomarkers** for inflammation, this new biosensor will enable earlier detection of inflammation.

Hold up, what's the difference between an analyte and a biomarker?

Analyte is a general term for any substance or molecule being measured or tested. A biomarker is a quantifiable sign, a substance or a process that is associated with a biological condition or disease (but see the entry for more about it!).

BIOMARKER

Biomarkers, or biological markers, are at once simple and complex. They are central to **health** and other diagnostics, and form a large part of our everyday lives whether we know it or not. In the broadest terms, a biomarker is a measurable characteristic that, if present, absent or present at certain quantities, can be interpreted as a sign of a condition, disease or abnormal (or normal) state of being.

If you're thinking, "Hey, that sounds kind of vague," hold your horses. *Calma aí.* Let's start with some examples.

Blood pressure. There's a reason nurses take a reading of this long-established biomarker at almost every doctor's visit. Blood pressure can be easily measured manually or with a device and changes in its levels can signal potential cardiovascular problems.

C-reactive protein. Think of it as our body's built-in alarm system and a key biomarker for inflammation. It goes off when there's inflammation, and can also help identify individuals with higher risk for coronary disease.

Blood sugar. Ah, sugar. Your body tries to kick it out, but sometimes it overstays its welcome. Type 2 diabetes *mellitus* is one of the most common chronic metabolic disorders, and it can be identified by levels of sugar in the blood.

Seems simple enough. What's the catch?

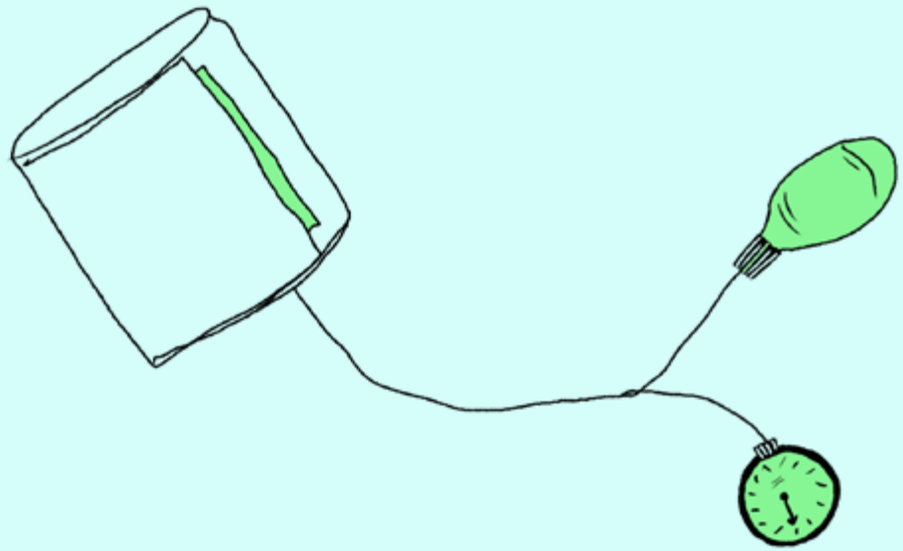
Well, for one, correlation is about the most difficult thing to prove in science. When talking about health, most diseases or health-related conditions are determined by complex interactions of factors. That's one reason why biomarkers are the result of extensive scientific and medical research, scientific consensus-building, and ultimately a multi-step qualification process by relevant authorities in different parts of the world.

Researchers work together to gather the evidence to show that a certain characteristic is associated with a specific health state. They then classify biomarkers according to their association, such as *predictive*, *diagnostic*, *monitoring*, *susceptibility*, among others.

Biomarkers have been increasing in importance over the past 30 years, not only in medical or health diagnostics, but also in drug development.

Drug development is a slow, costly and high-risk endeavour. When new drugs or medicines reach the clinical trial stage, tests must show that they are safe for people (and their 78-79 organs and 11-12 systems, depending on who you ask). Not a surprise: most drugs fail at this stage. Industry leaders, governments, start-ups and researchers alike hope that more qualified biomarkers will allow them to figure out earlier whether a drug will be a smashing success or sink, saving time and money. *Dindim! Ka-ching.*

The discovery of new biomarkers also allows for the creation of more sensitive, affordable and rapid biosensors to measure them. Ideally, this leads to two major benefits: patients get quicker and more accurate diagnoses, and the slow, expensive process of developing new drugs can be improved.



SCALE

There are kitchen scales and scales of justice. One is for measuring the ingredients in your cake, the other offers a metaphor for fairness in judgement. There are musical scales, which refers to the arrangement of notes in a music system. And, of course, let's not forget the fish scales (for more on that, check out **bio-inspired technology**).

In the dynamic but miniature world of biosensing, scale is really important for understanding the relative size of the various components, such as those inside a biosensor. Three relevant scales in biotechnology are the macroscale, the microscale and then the nanoscale.

All that you can see with your eye, including if you wear prescription-strength glasses, is on the macroscale. An easy way to remember where this scale begins is to think of the width of a single strand of hair. Anything that size or bigger is on the macroscale. (Yes, yes, different hair types have different widths. Curly, whirly, wavy, or straight, we're talking about the average here).

Meanwhile the microscale refers to smaller things that are between 1 mm (1000 µm or micrometres or microns) and 100 nm (nanometres). MEMS sensors and MEMS biosensors are on the microscale. **Microfluidic** chips are also on the microscale, although they are used to synthesize, analyse and manipulate particles on the nanoscale, which refers to much smaller stuff (between 100 nm and 1 nm). **Photolithographic DNA synthesis** is a microscale process, while individual DNA molecules are on the nanoscale.

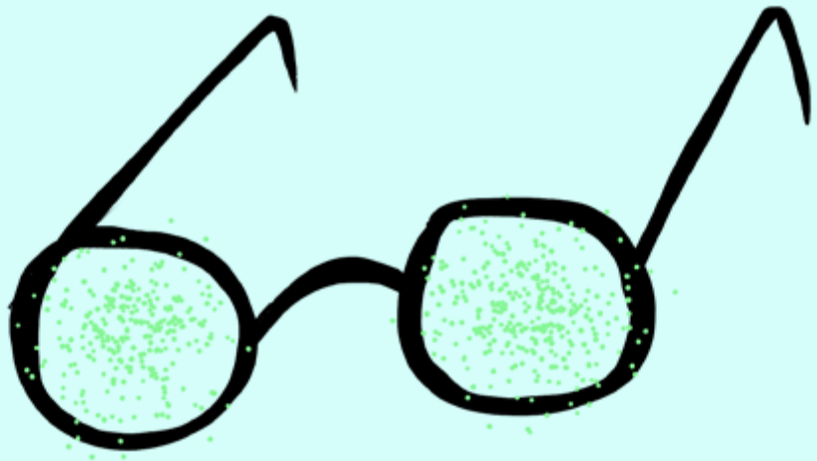
For more, see the nifty chart below:

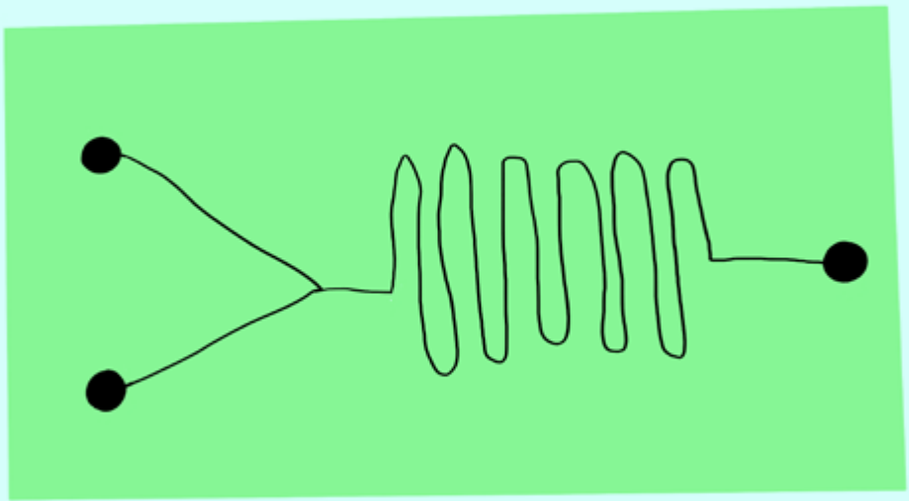
How to write it?	**Make it make sense!**	**Name something this size.**
Metre (m)	1 m = 100 cm	A guitar; the average 3-4 year-old child
Centimetre (cm)	1 cm = 10 mm	The height of a Lego, a staple
Millimetre (mm)	1 mm = 1000 µm	Mobile phone screen protector
Micrometre (µm, $10x^{6}$m) *also sometimes called a micron	1 µm = 1000 nm	Average bacteria; a spider's thread
Nanometre (nm, $10x^{9}$ m)	1 nm = 10 Å	A water molecule; a cell membrane
Ångstroms (Å, 10^{-10} m)	1 Å = 100 pm	The diameter of phosphorus, sulphur, and chlorine
Picometre (pm, $10x^{12}$ m	1 pm = 1000 femtometre (fm)	Protons; neutrons; the nucleus of an atom

That's not all friends. There's a lot of talk these days about scaling up. As in scaling up a business, or scaling up production, generally referring to increasing the size of operations or the number of units of a given item (say, sneakers) to be manufactured.

Industry demand and the desire to scale up the production of technologies like biosensors and **lab-on-a-chip** devices are often (but not always) linked to the scientific and engineering goals of scaling down the components to the microscale. That is, working with smaller and smaller pieces.

Take the BIOASSEMBLER project as an example: the **consortium** worked at the micro and nanoscales to find clever, **bio-inspired** ways to scale up the production of biosensors on silicon wafers, making them easier and cheaper to produce.





LAB-ON-A-CHIP (LOC)

Tiago's tiny lab-on-a-chip tests plasma proteins precisely.

(Faster) Tiago's tiny lab-on-a-chip tests plasma proteins precisely.

(Even faster) Tiago's tiny lab-on-a-chip tests plasma proteins precisely.

Tongue twisted yet?

Tricky to type, twisty to say, a lab-on-a-chip (LoC) is a category of device designed to replicate the diagnostic functions of a laboratory on a miniature scale. They are tiny tools that can do lots of things, like mixing and analysing blood or water, all on a small chip the size of a credit card.

How to make one: take a laboratory, shrink it, shrink it a little bit more and now affix it to a semiconductor chip: *presto!* You've got yourself a lab-on-a-chip.

This would be easy if we had a shrink ray. In reality, the construction of lab-on-a-chip devices is complex — the result of over 30 years of innovation in **microfluidics**, **photolithography**, semiconductor manufacturing, 3D printing and more.

A biosensor is *not* a lab-on-a-chip. However, biosensors can be integrated into lab-on-a-chip devices as one of the many components of that miniature lab. Sensors are often central components of LoCs, because they allow for the measurement and analysis of biological and chemical substances, as in the case of biosensors and chemical **MEMS sensors** respectively.

Lab-on-a-chip devices are currently being used in diagnostics, drug development and for DNA analysis. Even a COVID-19 test is a kind of a lab-on-chip device, only it is paper that draws the sample across the strip where a reaction occurs if the analyte is present. Other, more complex lab-on-a-chip devices, like organ-on-a-chip devices are in the process of being innovated and have been commercialized to a limited extent. That's right, we've got front row seats to the birth of this technological baby — someone pass the popcorn and a pacifier!

There are expectations that lab-on-a-chip devices will play an increasingly important role in the transformation of current diagnostic and laboratory technologies. The overarching goal driving these innovations is to design a lab at the miniature scale that is faster, more precise, more affordable, mobile, automated and that only requires a miniscule sample. There's a lot of work still to do to get there. For more specific examples of different kinds of lab-on-a-chip devices, see **x-on-a-chip**.

X-ON-A-CHIP

Plant-on-a-chip.

Sea-on-a-chip.

Organ-on-a-chip.

Placenta-on-a-chip.

Lung-on-a-chip.

What comes to mind? Cyborgs? *A Brave New World?*

Actually, we're still talking about **lab-on-a-chip** (LoC) devices (check that entry, if you haven't already). X-on-a-chip is a naming pattern used by scientists and engineers to describe specific kinds of LoCs. They contain compartments that aim to replicate the "x", whether that's the sea, a plant, a human lung, a placenta or another organ or organism, in order to better study it.

The most common examples are organ-on-a-chip (OoC) devices. Don't worry, there are no actual organs on these chips – at least not in the sense of whole hearts, brains, lungs or kidneys. Instead, these experimental LoCs are designed to mimic the structure of a specific organ. They integrate 3D living tissue into **microfluidic** structures that imitate the flow of blood and oxygen, keeping the cells alive.

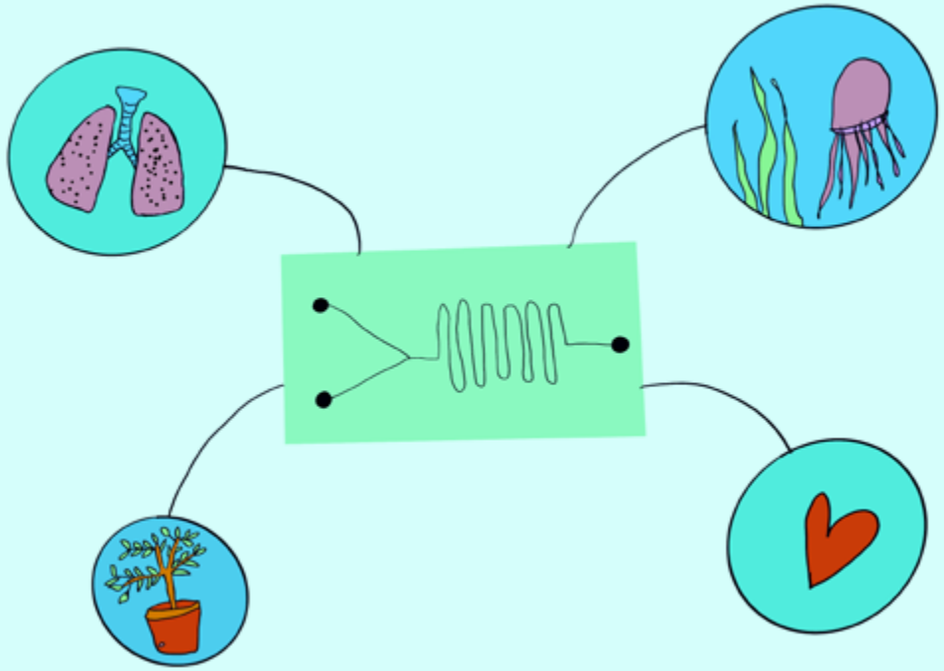
One of the main ideas behind OoC devices is to build a proxy for research that is not human (nor any other animal), but instead mimics the physiological complexity of organs in the human body. These miniature devices provide a major boost for developing new medicines. By replicating key functions of the human body, they allow researchers to create more accurate models of how diseases affect different groups of people.

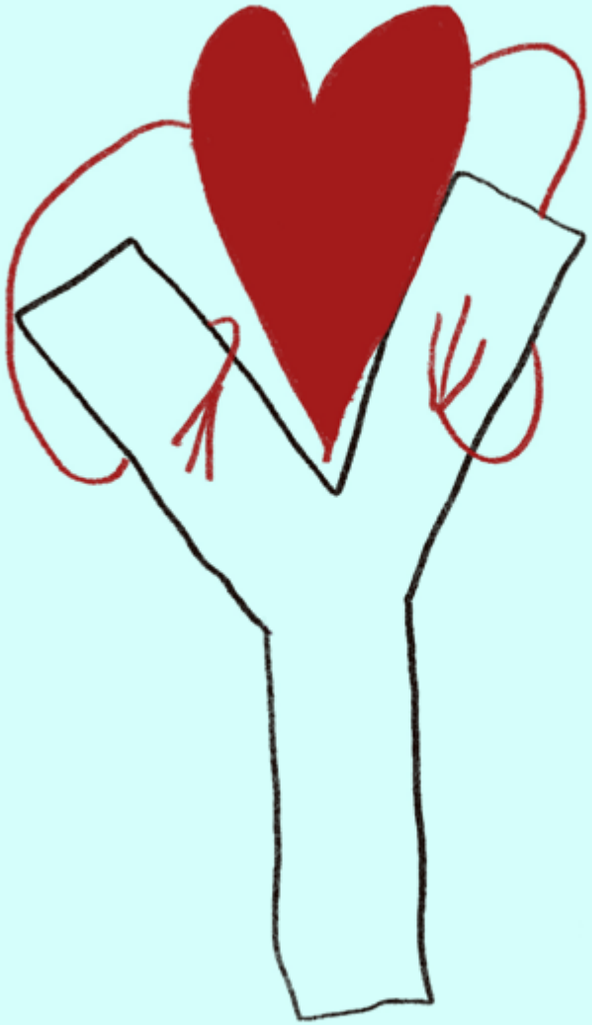
This means that early-stage testing becomes much more reliable at predicting how a drug will actually work in people. As a result, these devices can be used to test a new drug's effectiveness and safety far more realistically than was previously possible. What happens after one dose? Two? Are the drugs effective?

Think, for example, of protected groups such as pregnant people or children. They are often excluded from clinical research studies, which makes it challenging for researchers to understand the impact of drugs and interventions on them, and also on the foetus, placenta, and neonates. The aim of a device such as a placenta-on-a-chip is to more quickly and cost-effectively determine whether or not a drug or intervention will be viable prior to moving forward to risky, costly human and other animal trials.

There are ethical benefits and drawbacks to organ-on-a-chip devices. As with animal-free **recombinant antibodies**, the use of OoC devices can reduce the need for animal testing. Yet, for this to be achieved, devices need to be standardized, and legislations and protocols need to be updated, ideally internationally.

Other ethical considerations include consent for cell donation (see **cell lines**) or the moral status of life-like models. As with the case for biotechnology, a **critical lens** on x-on-a-chip will also help us to identify and analyse ethical issues related to the increased use of this technology.





ANTIBODIES

A good joke, a film with a moving story or a disgusting smell. It's hard not to react to things like these. Laughing, getting emotional and feeling annoyed are natural reactions of our body. They are signals telling us if something is going well... or maybe really wrong.

If something strange enters our body, we rely on antibodies to react. Antibodies are natural defence responses produced by our organism against invaders. These unwelcome visitors are called antigens and can include viruses, bacteria, allergens or toxins.

Antibodies are proteins that can bind to specific regions of the surface of antigens and neutralize them in various ways. For example, antibodies can prevent viruses from entering host cells or neutralize toxins produced by bacteria.

Since antibodies are great at identifying invaders, they have become key allies in detecting certain substances.

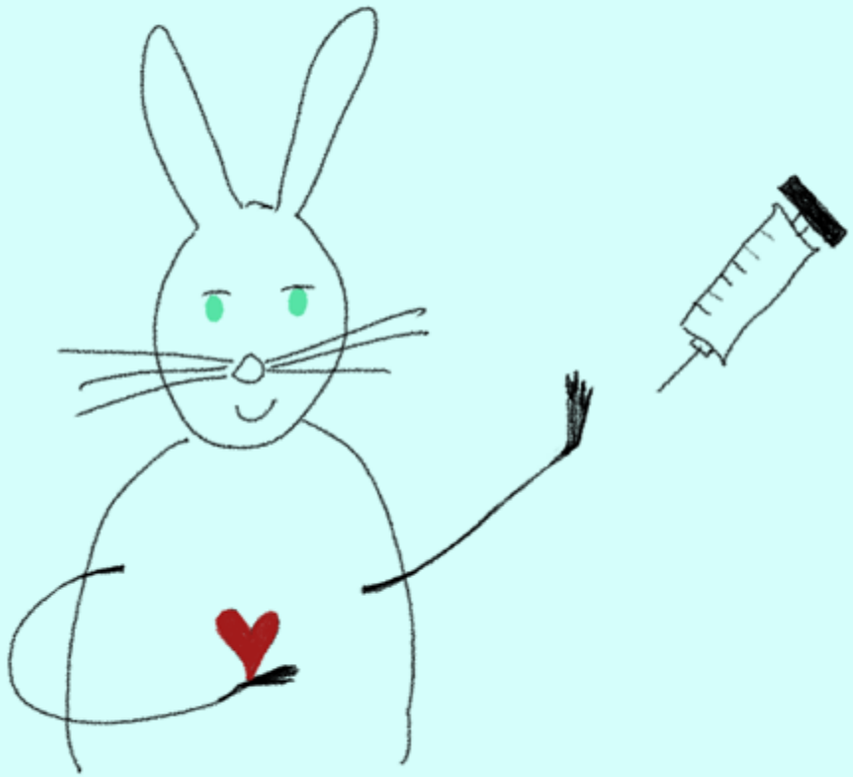
Imagine we want to know if someone has COVID-19 or the common cold.

Today, biosensors are widely used for this type of detection. They are available as rapid home tests and found in large laboratories. These devices detect target substances using a biological element, called a bioreceptor. And guess what? In many cases, antibodies are the ideal choice for the role of bioreceptor.

In practice, this is how it works: biosensors use antibodies as capture molecules on the surface of the device. The goal is to check if antibodies' molecules selectively bind to the target component (and *only* that target), for example, binding to proteins at the virus surface.

Antibodies are represented in the shape of a "Y". What happens is that their ends, known as variable regions, work together to bind to the identified antigen. So, when a **sample** containing the virus is added, the viral molecules will bind to an antibody.

This special reaction creates a clear signal of the presence of the virus, and the perfect opportunity to use **antibodies in biosensors** (go check that entry!).



RECOMBINANT ANTIBODIES

A major challenge for scientists and engineers, especially in biotechnology, is advancing science while reducing animal suffering and making processes more environmentally friendly and sustainable.

In the production of biosensors, that is a big deal, because biosensors rely on biological materials like **antibodies** to function.

Traditionally, antibodies have been obtained from animals by injecting them with a foreign antigen to stimulate their immune system and trigger the production of antibodies, which are then isolated for use in biosensors. In this process, while large animals like horses and goats can provide blood in specific time frames, smaller animals like rabbits and mice might not survive.

For some time now, scientists have been working on a solution to this problem using **recombinant DNA technology**. This is a method for altering segments of DNA outside a cell or living organism to obtain improved and desired characteristics. This technology makes it possible to create what we know as "genetically modified organisms", or recombinant proteins.

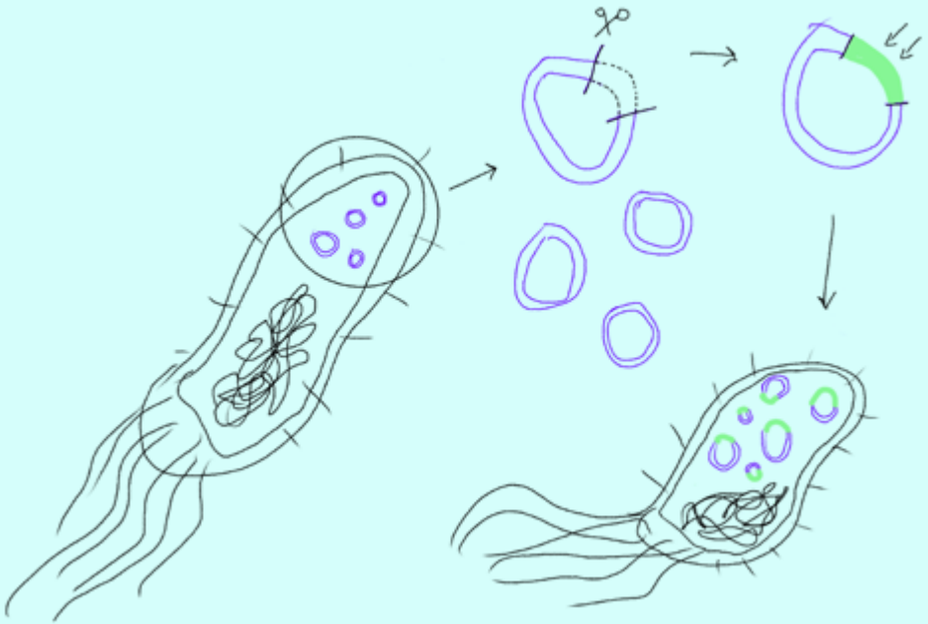
And one of the many applications of recombinant DNA technology is the production of fully recombinant antibodies. These antibodies can be produced in the lab by cell culture, a process of growing and maintaining cells outside their natural environment.

How does it all work? The first step for production in cell culture is to obtain the DNA sequence of the to-be-discovered antibody, the antibody you want to create. This is done using antibody phage display, a method of selecting antibodies presented by bacteriophages from an antibody library – a set of millions to billions of different antibody sequences isolated from human blood.

Besides replacing animal-derived antibodies, an important advantage of recombinant technology is the possibility of modifying antibodies in different ways to make them more suitable for biosensors. This includes creating different protein tags utilized to attach the antibodies to the sensors' surface.

Another super advantage of recombinant antibodies is that their performance is always predictable. Unlike animal-derived antibodies, they do not require individual testing and standardization. Recombinant antibodies have a specific binding affinity, and their concentration can be measured. This allows for a precise production process.

If all this sounds excellent and super innovative, that's because it is! What are your thoughts on the ethical and scientific impact of recombinant antibodies?



RECOMBINANT DNA (RDNA) TECHNOLOGY

Recombinant is an adjective used to describe something that has been *combined again*, or re-combined. It is especially applied to DNA, as in *recombinant DNA* (abbreviated as rDNA), to refer to DNA that contains genes from more than one source.

rDNA is created by inserting a gene of interest into a host cell. To do this, technicians use a vector, often a plasmid (a small ring of DNA found in bacteria), and *cleave* or split it open. After isolating the gene of interest, this gene is inserted into the gap in the plasmid, and sealed with an enzyme called DNA ligase. To help visualize this process, imagine cutting a microscopic rubber band with a pair of molecular-sized scissors, leaving two exposed ends. Technicians glue the gene of interest between these two "sticky ends", creating a full ring once again. This is how recombinant DNA is made.

Next, the plasmid (the rubber band in this scenario) is returned to the bacteria where it begins to replicate on its own. As the ring of plasmid replicates, so too does the gene of interest that had been cut and pasted into the plasmid!

Recombinant DNA technology has been used to produce recombinant or "human insulin" since 1978. In fact, recombinant insulin was the first approved biotechnology drug, created to meet the demand for this life-saving hormone. Prior to this breakthrough, insulin was only derived from animals such as pigs and cows. The shift from animal-based insulin to recombinant "human insulin" in the late 1970s and 1980s represented a significant transformation in the production of insulin.

Beyond insulin production, recombinant DNA technology has enabled the creation of vaccines, such as the hepatitis B vaccine, through the insertion of viral genes into yeast cells! It is also widely used in agriculture to develop genetically modified crops that show improved resistance to pests, disease and environmental stress such as drought. Its use has also sparked **ethical** and environmental debates concerning the commodification and patenting of seeds and biotechnologies by private corporations.

Another transformation in production is currently underway as biotechnologists explore how to produce recombinant antibodies to reduce the current dependence on animal-derived antibodies for drug production and scientific research. For more about this transformation and why it's important check out **recombinant antibody technology**.

ANTIBODIES ON BIOSENSORS

Biosensors differ from other sensors because they include a biological element called a bioreceptor. And **antibodies** possess the attributes that are ideally suited for this role. Let's take a closer look at why:

For starters, something cool about antibodies is their modularity. Each antibody has two main regions: a constant region and a variable region. The variable region contains hypervariable regions that differ greatly between antibodies. This makes antibodies selectively bind to antigens, which can be proteins on the surface of a virus or a toxic substance such as cocaine or a pesticide. The list goes on, but the bottom line is that antibodies protect our health by recognizing and binding to potential threats to our immune system.

Another skill is that as well as doing the job itself, antibodies can act as mediators between an antigen and the immune system. They do so by recruiting other parts of our immune system for the battle. For example, they can activate natural killer cells to fight antigens.

So how are antibody features used in biosensors? Antibodies are chemically attached to the sensor surface so they can selectively bind to a target.

Let's take the example of a famous, simple and precise biosensor: the rapid pregnancy test. In this case, the target is a hormone called hGC, found only in the urine of pregnant women. If hGC is present in a sample, it will bind to specific antibodies that only bind to hGC molecules. This interaction will be signalled by a colour change in the test.

But how does the testing *actually* work?

First, a conjugate of an antibody and a colouring agent is placed on the surface. The sample is then dropped, and the antibody binds to hGC present in it. The liquid (with the antibody and bound sample) moves along the test strip until it reaches the test and control line. At the sample line, there is a second "fixed" antibody that also binds to hGC and therefore binds to hGC and the conjugated antibody. The result is a "sandwich" with the fixed antibody + hGC + conjugated antibody. That arrangement means the result is positive.

However, if no hGC is detected in the sample, the colour is washed away, indicating a negative result.

But you may be wondering: where do antibodies used on biosensors come from? Antibodies are produced biologically, and most of the ones used in biosensors are obtained from animals through a two-step process: immunization of the animal and isolation of the antibodies. But this reality has changed, thanks to **recombinant antibody technology** and synthetic proteins — and this transition represents a huge step forward in reducing animal suffering in science.

CELL LINES

Cell lines are a revolution. And, like most revolutions, this one arrived via a troubled path.

Date: January, 1951. Place: Maryland, USA. A young African American woman named Henrietta Lacks visited Johns Hopkins Hospital complaining of what she described as a "knot" in her womb. Four months earlier, she had given birth to her fifth child, but it had not been easy. A biopsy of this cervical "knot" proved to be cancerous. During her treatment, **samples** of her cervical tissue were passed on to a cell biologist without her knowledge or consent – or that of her family. Henrietta died of cancer in August of 1951.

Mary Kubicek, a laboratory technician and researcher working with the cell biologist George Otto Gey propagated Henrietta's cells. Whereas most cells die, to the astonishment of all Henrietta's cells doubled every day due to a mutation. These cells, known as HeLa cells (for *He*nrietta *La*cks), became the first immortalized cell line to grow in a laboratory and revolutionized medicine and science.

In fact, the National Institute of Health (NIH) of the United States maintains a database of research on and with HeLa cells, so vast is the extent of their significance to science. To list just a few highlights, HeLa cells have been used to:

— Grow poliovirus for scientific research, and aid in the development of the polio vaccine.
— Understand the effect of x-rays on human health.
— Develop novel cancer research methods.
— Study the impact of radiation on astronauts in outer space.
— Develop treatments for cancer and blood disorders.
— Understand how salmonella and tuberculosis infect the body.
— Learn how HIV and Ebola infection works, contributing to the development of treatments.
— Better understand aging.

And much, much more.

Despite the many advances made using HeLa cells, for decades her family did not know about Henrietta's role in research, and had never given consent for the use and study of her cells. Working with the journalist Rebecca Skloot, author of *The Immortal Life of Henrietta Lacks* (2010), her family have pushed for the recognition of Henrietta as a person, for reparations, racial justice in medicine and scientific research and transformations to **ethics and research** protocols around consent and **data privacy**.

HeLa cells are not the only immortalized cell line. HEK293 is another commonly used cell line, derived from a dead human embryo in the early 1970s. It was in molecular biologist Alex van der Eb's laboratory in the Netherlands that the young researcher Frank Graham managed to turn these cells immortal. He modified them so that they could continue dividing. "HEK" stands for *Human Embryonic Kidney* and 293 for the lab's number, hence HEK293.

One of the most important discoveries made using the HEK293 cell lines have been the new COVID-19 vaccines. In the BIOASSEMBLER project, researchers also used HEK293 cells to produce the antibodies used for the novel assembly technology (see **synthetic DNA-guided self-assembly**).

ANTIBODY LIBRARY

Think of a library and you might picture books, the smell of old paper and the loveliest (or grumpiest) librarian. But these are not the only kinds of libraries around!

Antibody libraries are an incredible tool for research. These curated collections of antibodies allow scientists to search and quickly identify the precise antibody they're looking for — whether that's an antibody that targets a specific antigen or one that has unique binding or other functional properties.

There are many different kinds of antibody libraries, based on the type of antibody they contain. For example, there are libraries that contain only recombinant synthetic or **recombinant antibodies** of naïve origin. There are also libraries of immune antibodies (immune libraries), which contain antibodies directly from donors who were exposed to the antigen.

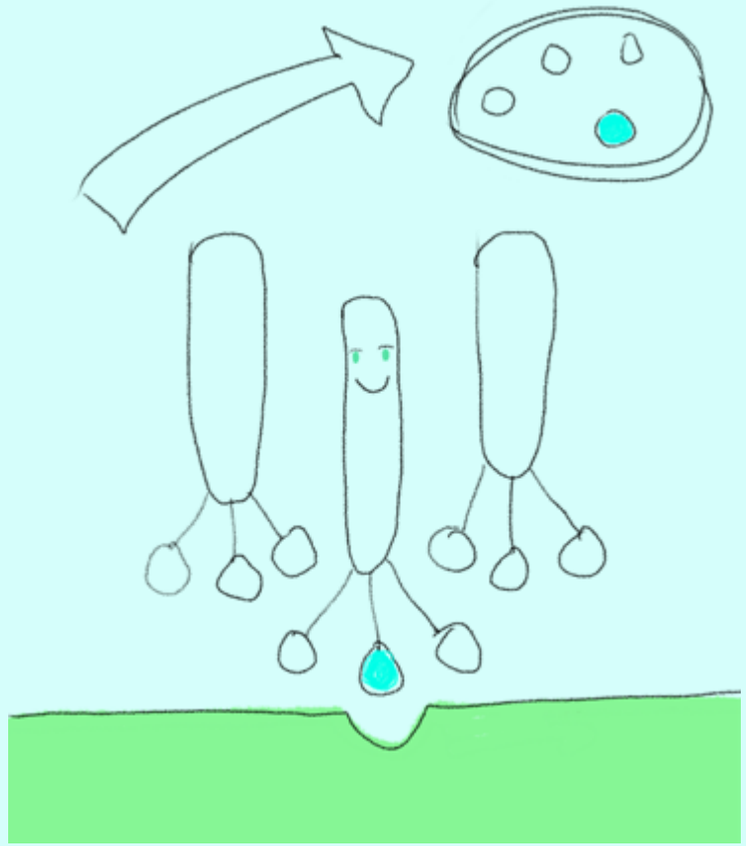
The library doesn't contain the antibodies *per se*, but rather their blueprints in the form of DNA sequences. Each DNA sequence contains the instructions for how to make the antibody. And can you guess where these antibody gene sequences are produced? Yes, in **cell lines** (or cell cultures) like the HeLa or the HEK293!

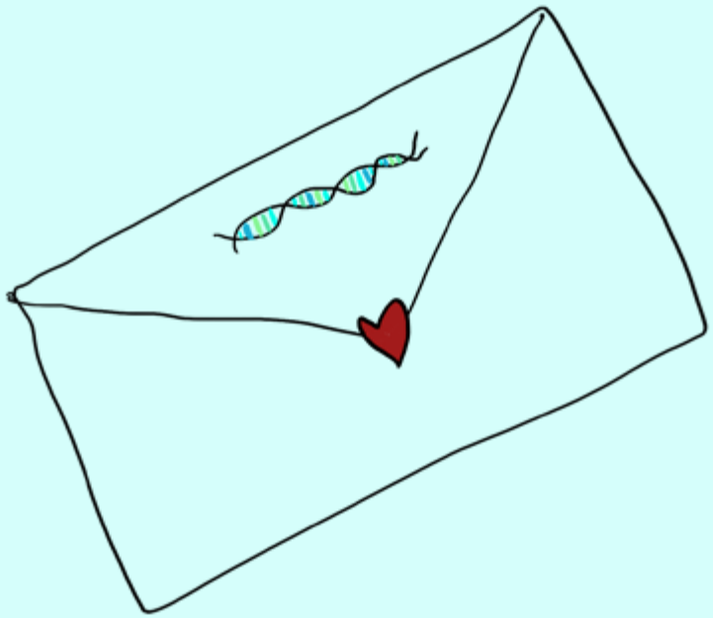
When searching for an antibody with a particular function or that best targets a virus, scientists go to the antibody library and search for blueprints that might be a good fit. They then put these blueprints (the DNA) into cells (of bacteria, yeast or a particular type of virus called bacteriophages, or phages for short). These cells then read the DNA and make the antibody. Phages are especially cool because after scientists insert DNA fragments into them, they display the antibody on their surface. This technique is called phage display.

This process of finding new antibodies either to fight a virus, bacteria or to develop medicines or diagnostic tools like biosensors, is often called antibody discovery and is like a treasure hunt that begins in antibody libraries. For example, good biosensors require specific and reliable antibodies that bind only to the target **analyte**. Antibody libraries allow researchers to search through gazillions of antibodies to find which will bind only to the analyte and that are stable enough to work in a device.

Antibody libraries have played an important role in scientists' ability to fight COVID-19. Once researchers identified the spike protein as the key site to stop the virus from infecting cells, the hunt was on for antibodies that could bind to that protein. Researchers used antibody libraries to identify possible candidates, eventually identifying the best antibodies to develop therapies and diagnostics. Since viruses are constantly evolving, so too is antibody discovery (and that's why there's a new flu vaccine every year!).

Unlike public libraries, most antibody libraries are not free. Many biotech and pharmaceutical companies maintain commercial antibody libraries protected by **Intellectual Property** laws. Researchers or institutions typically pay for licenses to access these libraries or for in-house antibody discovery services. There are, however, various efforts by non-profits and universities to create open access (see **Open Science**) antibody libraries to make this technology and knowledge more accessible!





DNA ZIP CODE

Ever wondered how we can guide things in the microscopic world to find their way? Scientists and engineers have developed a system surprisingly similar to our own postal service, but instead of a zip code on a letter, they use a DNA zip code.

Think of it like this: a regular zip code on an envelope tells the postal service where to deliver it. In the world of nanotechnology, a DNA zip code does something very similar. It's a short, unique piece of DNA that acts as a tiny address, guiding molecules to a specific spot on a surface, like a silicon chip. But it's not just about the address; it's also about identity. Much like a barcode uniquely identifies a product, each DNA zip code has a unique sequence. Only a molecule carrying the matching complementary "barcode" DNA strand can bind to it. This brilliant system is the key to a process called **DNA-guided self-assembly**.

This principle is simple (*beautifully simple*, we might say). It relies on the natural tendency of two complementary single DNA strands to pair up and form a double helix. By attaching a specific DNA strand to a protein (like an antibody), we can guide it to find its complementary partner — the DNA zip code — which has been immobilized at a precise location on a chip surface.

So, how are these DNA addresses created on a chip? The BIOASSEMBLER project used a technique called photolithography, which is a bit like printing with light (but go check the entry **photolithographic DNA synthesis** for more on this). This allows to "print" vast arrays of different DNA zip codes onto a silicon **wafer** with incredible precision. We're talking even sub-micron accuracy! (No idea what that is? Check out **scale**.) This creates a sort of "molecular switchboard" on the chip.

The real magic happens when DNA-tagged biomolecules are introduced to this switchboard. They automatically "self-assemble", with each molecule finding and binding only to its specific, complementary zip code. This allows for the construction of complex sensor arrays with exquisite accuracy and speed, all at once across an entire wafer.

What's more, this technology offers amazing flexibility. For example, producing chips that have just the DNA zip code layer. This means the end-user can decide which DNA-tagged proteins or other biomolecules to add later, simply by introducing their chosen set of self-assembling binders when they're ready to run their experiment. It's a powerful way of bringing the worlds of nano- and biotechnology together, creating a highly efficient and customizable manufacturing platform for building the next generation of biosensors.

Amazing, right? And this is just only part of the innovative work done in BIOASSEMBLER!

WAFER

In the miniature world of biosensors, a wafer is not a biscuit and a chip is not a salty snack.

A "wafer" refers to a silicon wafer, or "Si-wafer" for short. Si-wafers are super-thin, super-flat disks of crystalline silicon that are most commonly used as semiconductors in electronic devices. They look like small, shiny CDs or DVDs — but without the hole in the middle!

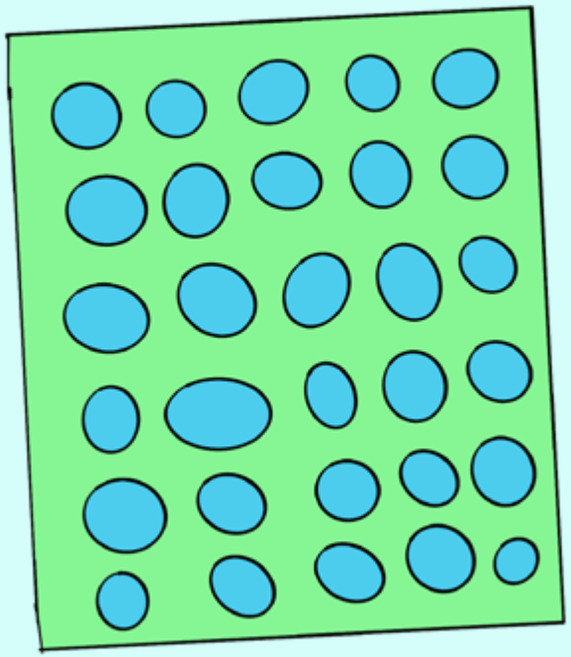
You might not know it, but Si-wafers are all around us. They are in our computers, smartphones, televisions, cars, and even solar panels. They are also used in micro-electro-mechanical systems (MEMS) sensors. If you've ever been driving and had the misfortune of your TPMS — the "Tire-Pressure Monitoring System" — light turning on due to low air pressure or a punctured tire, that is evidence of a silicon wafer-based **MEMS sensor** working for you!

But how do wafers actually work?

Think of a silicon wafer like the base of a sandwich or a cake. It is the bottom layer or substrate that everything else is built on. Using techniques such as **photolithography**, integrated circuits or "chips" are etched onto the wafer's surface and tiny transistors are patterned on the chips. This delicate process must take place in **clean rooms** to avoid contamination. These miniature electrical switches are what make devices such as computers work. Each transistor can be turned on or off individually, which is how binary information (0 and 1) is stored and processed. The more transistors are on a single chip, the more data the silicon chip can process, and at a higher speed.

Since the 1980s, Si-wafers have gotten larger in diameter (from around 15cm to 30cm), while chips or "microchips" and transistors have gotten smaller. This means that more chips can be etched onto a single Si-wafer, leading to a greater chip density. The latest Apple M2 chip, for example, is only a few millimetres in size and has 20 billion transistors on its surface! This is possible because the components on the microchip, the "chip nodes", are as small as 5 nanometres. For comparison, a red blood cell is approximately 7 000 nanometres wide and imperceptible to the naked eye. Powerful optical microscopes or "microsphere nanoscopes" enable humans to see at this scale. What this means is that incredibly powerful chips now fit into the smallest gadgets such as smartphones and watches.

Si-wafers are the building blocks not just for computer chips, but for all kinds of tiny sensors. Bioengineers are now using them to make biosensors that can detect molecules linked to health and disease. Imagine printing **antibodies**, the body's natural detectors, right onto a microchip made from a silicon wafer!



SENSOR ARRAY

An *array* is an organized display or arrangement of things. For example, the Joanina Library at the University of Coimbra has an *array* of rare historical manuscripts, just like this book presents an *array* of terms and definitions. In computer science, an *array* is a data structure where each piece of information has a specific position.

When talking about sensors, including **MEMS biosensors** and **MEMS sensors**, a sensor array is a group of sensors arranged in a specific pattern on silicon **wafers**. These sensor arrays are created in clean rooms using high-tech semiconductor manufacturing techniques, like **photolithography**, which is similar to how microchips are made. This is one of the first steps in building a biosensor!

Now, let's look at one specific example: acoustic microresonator arrays.

You might already know now that **acoustic microresonators** are a type of sensor technology (You don't? Go read the entry!). These resonators detect changes in mass when biological molecules (the analyte) bind to the sensor's surface. This change is then measured electronically. Since tens of these sensors can fit into an area just a few millimetres squared, they're perfect for creating tiny but powerful biosensors.

To create a biosensor that uses acoustic microresonator arrays, the resonators need to be placed onto an Application-Specific Integrated Circuit (ASIC).

A what!?

An ASIC is a special kind of computer chip designed to do one job extremely well, like processing financial transactions or powering a smartphone. Since it is made for a specific task (instead of handling many different tasks like a regular computer chip), it is faster and more efficient.

Now, imagine you're making a *bolo de bolacha* (a delicious Portuguese layered cookie-cake). The first layer is the silicon wafer, which is etched using photolithography to create the ASIC. This is like the cookie base of the cake. Next, the acoustic resonators are carefully placed on top (like the creamy filling in the cake) using **thin film deposition**. Together, these layers form the substrate, or the foundation layer for the next layers or steps, the placement of antibodies on the biosensor.

ACOUSTIC MICRORESONATORS

They're tiny, they're mighty, they're: acoustic microresonators!

Oh, is the text too small? Let's increase the font size and try again.

They're tiny, they're mighty, they're: acoustic microresonators!

Ahhh, that's better. Some things are too small to see or hear. Printing in larger fonts, raising the volume on a TV, using magnifying glasses or hearing aids are all techniques that allow too-small sights and sounds to be made larger or louder so that our limited human sensory capacities can be enhanced.

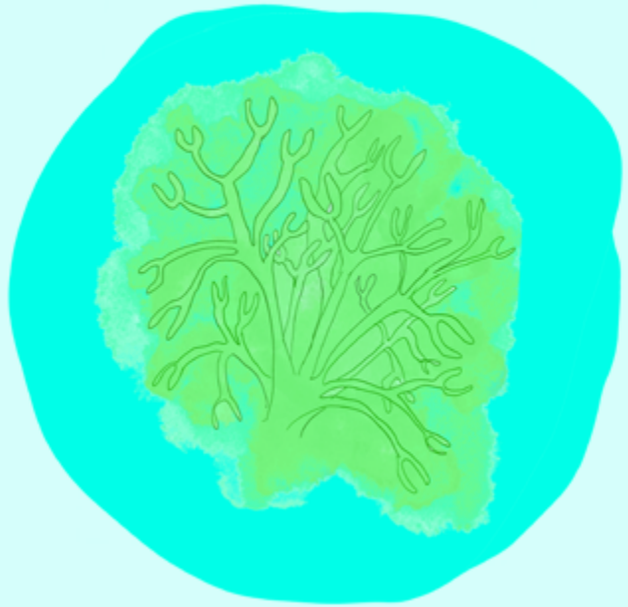
Acoustic microresonators are a kind of device that allows for the detection of miniscule changes in mass, such as those that occur inside of an antibody-based biosensor. In such a biosensor, antibodies are chemically attached to the surface of the sensor. When the **antibodies on the biosensor** bind with an analyte (the substance that is being tested for or measured), a change in mass occurs. When mass is added to an acoustic microresonator that has been built into a biosensor, there is a decrease in the acoustic resonator's resonant frequency (GHz). This is the frequency at which a system tends to oscillate or vibrate. This change in frequency is what signals the detection of the analyte. The change is measured by an Application-Specific Integrated Circuit (ASIC; for more on this, see **sensor array)** that is integrated onto the silicon chip or wafer alongside the acoustic microresonator.

This leaves the question of *how* acoustic microresonators end up in biosensors in the first place?

Let's back up a little bit here.

Silicon **wafers** are repeatedly coated with thin films of material and etched using **photolithographic** processes in **clean rooms** to produce circuits (application-specific integrated circuits to be precise) that are monolithically integrated into the chip. That's a fancy way of saying that the circuit is built into the chip, it is not attached or affixed using glue or any other kind of adhesive mechanism. This is a well-established semiconductor fabrication method called CMOS, which stands for Complementary Metal-Oxide-Semiconductor.

Acoustic microresonator sensor arrays are then deposited on top of the ASIC or integrated circuit using what is called "ScAlN thin film deposition." That's right, this is too complex for one entry. Go check out **thin film deposition** to learn more!



P.S. Well, we wonder...who invented all these acronyms? Why are they so many and so hard to say? Were the linguists consulted?

P.P.S. Well, each acronym has a story. FACT: the Radio Corporation of America (b.1919, d. 1987, RIP) trademarked the more fun-to-say COS-MOS, driving competitors to come up with another name. Consensus formed around CMOS in the 1970s. But don't worry, it's still fun to say: SEA MOSS (anyone else getting green fuzzy feelings?).

CLEAN ROOMS

Clean rooms are far more than a tidy space: they're highly controlled environments where nano- and micro-scale electronics are manufactured, including sensing elements for biosensors. Clean rooms are also used in the production of flat screens for smartphones, pharmaceuticals and in hospitals — where the very first "clean rooms" were invented for performing operations in sterile environments.

These tightly engineered facilities allow for the precise control of temperature, pressure, air flow and even the number of particles in the air. They are designed to keep things *out* (such as dust or airborne viruses) and, in some cases, to keep things *in* (as in the case of hazardous materials).

Clean rooms used in the manufacturing of sensor elements for biosensors must also be sterile, or free of bacteria and other microorganisms. They are essential for the manufacturing of many electronic devices and sensors because a single speck of dust can impact the performance of a microelectronic chip! But they are also costly to build, operate and maintain. For this reason, they are not so common and in Europe they are often supported financially by national governments, the European Union and industry user fees.

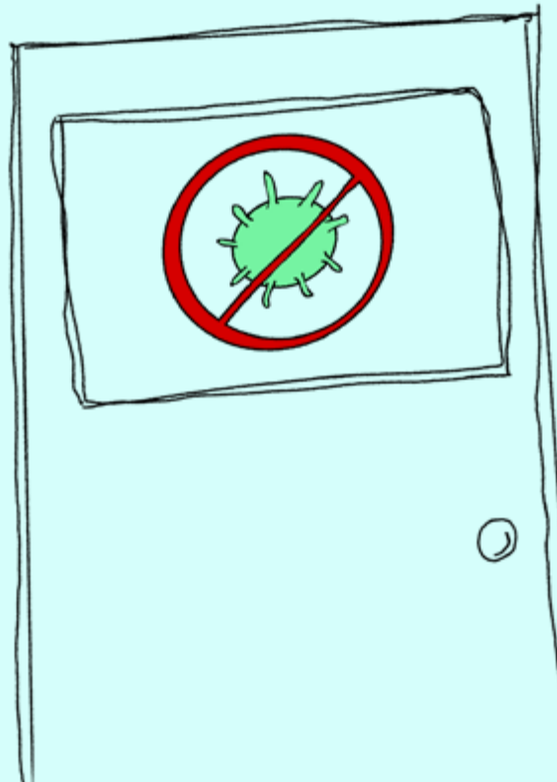
Let's look at two really cool clean rooms in Europe:

Micronova in Espoo, southern Finland, is the largest cleanroom in northern Europe, run by Aalto University and VTT Technical Research Centre of Finland, a state-owned research and innovation partner. With an area of 2600 m², this facility is approximately double the size of an Olympic swimming pool. It is packed with sophisticated machines for the production of micro-, nano- and bio-technologies using a range of production techniques such as **photolithography** and Atomic Layer Deposition (ALD).

The International Iberian Nanotechnology Laboratory (INL) in Braga, northern Portugal, also has a large clean room with an area of 1200 m² for facilities and equipment. Founded and managed jointly by the governments of Portugal and Spain, with support from the European Union, INL is a hub for nano- and biotech research, science and even art! That's right, the INL opens its doors to offer artistic residencies to artists who use their work to **communicate** and contribute to scientific findings.

Clean rooms aren't exclusive to research facilities, they're also a key part of large industries. However, while research clean rooms like Micronova and INL are designed for flexibility and experimentation, industrial clean rooms tend to be highly specialized. Companies in fields such as electronics operate their own ultra-clean environments, but these are typically optimized for efficiency and consistency rather than open-ended discovery.

Think of it this way: industrial clean rooms are like high-tech assembly lines, producing the same perfected product at scale, while research clean rooms are more like innovation labs, where scientists can experiment, refine, and push the boundaries of technology. Both are crucial, but only one is built for discovery!



PHOTOLITHOGRAPHY

The name itself gives us some clues: photo (meaning light), litho (stone), and graphy (writing). These Greek-origin words come together to convey the meaning of the term, which is a *form of printing or etching patterns onto a surface using light.* Photolithography has numerous applications, including the large-scale production of microchips for electronic devices.

Manufacturers use advanced photolithography machines to etch integrated circuits (also known as ICs or "chips") onto silicon **wafers**. And bioengineers are also experimenting with photolithography to print DNA onto silicon wafers.

This technique has been around since the 19th century. Back then, photographers coated metal plates with "Bitumen of Judea", a tar-like substance used as a pigment since antiquity. They would then expose the Bitumen-coated metal plates to light, through a negative. The Bitumen exposed to light would harden, while the unexposed Bitumen remained soft. After washing the plate, the desired image would remain on the plate, ready for printing!

Contemporary photolithography uses a similar process, but with new materials, machines and in very particular places — **clean rooms**.

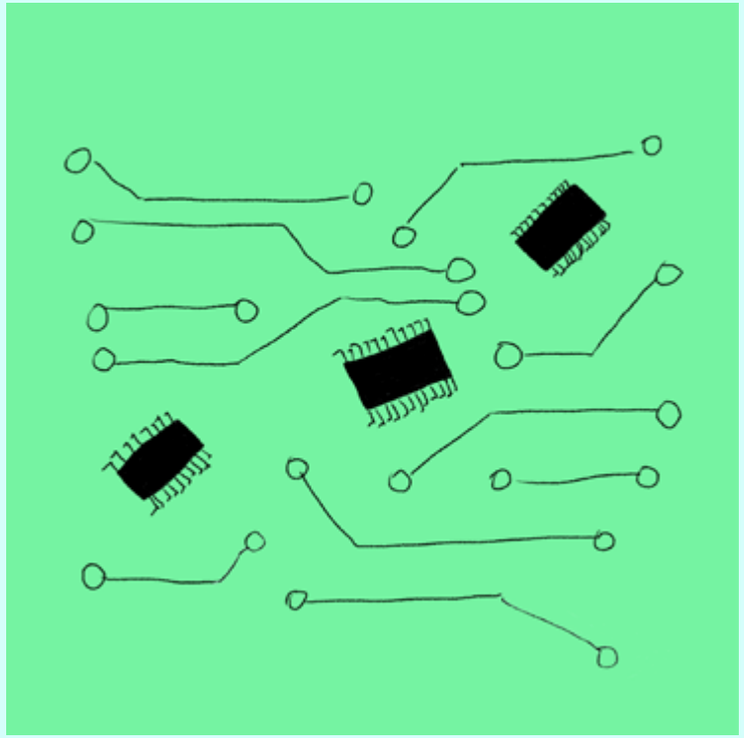
Let's explore how photolithography works:

The process begins when a technician places a silicon wafer into a small machine called a spin coater. A few drops of liquid photoresist, a light-sensitive material, are then added to the surface. This machine then spins the wafer really fast to get an even coating — all in 30 seconds! After a quick bake in an oven-like machine, the thin layer of photoresist hardens.

Next, the wafer is inserted into a photolithography machine, and the photoresist is exposed with light. Most machines require the insertion of a photomask, which is a plate that allows light to pass through an intended pattern (like the negative in our historic example). Then, the wafer is put in a developer solution that removes the photoresist from the exposed areas.

By repeating several times the **thin film deposition**, photolithography and etching steps, complicated multilayer structures can be formed which perform the desired electronic functions required in the designed device such as IC chips in the core of mobile phones or any modern electronic devices!

A state-of-the-art photolithography tool can cost tens of millions of euros. Engineers are also developing faster, cheaper techniques like maskless photolithography, which skips the need for photomasks. From smartphones and medical devices to biosensors and **MEMS sensors**, photolithography shapes the world around us, one microscopic pattern at a time!



PHOTOLITHOGRAPHIC DNA SYNTHESIS

As you can read in the separate entry named **photolithography**, this term refers to the process of using light to create patterns on a surface. Well, light can also be used to build DNA microarrays.

A microarray is a diagnostic tool containing thousands of DNA, RNA, or proteins arranged in a pattern, usually on a glass surface or substrate. Microarrays are used to analyse many analytes at once. Now imagine you want to build a microscopic detector, a biosensor, that can spot a specific piece of DNA from a virus. To do this, you need to create a tiny "trap" made of a matching DNA sequence. If the target DNA is present in a sample, it will get caught in your trap and send a signal.

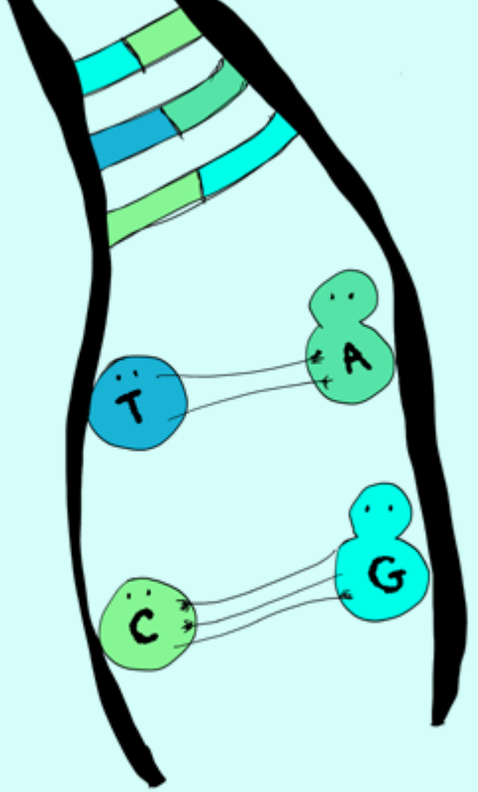
Photolithographic DNA synthesis is a clever way to build millions of these different DNA traps on a single, tiny chip. It works by using UV light to "write" the DNA sequences on a surface through consecutive nucleotide couplings.

A nucleotide is the basic building block for DNA and RNA. DNA is made of four chemical "letters": A, C, G, and T. To build our DNA traps, these letters need to be added one by one. Each letter comes with a light-sensitive cap that acts as a blocker, preventing any more letters from being added on top. Nucleotide coupling is a chemical reaction that links the nucleotides to each other and to the functionalised surface where the DNA strands are being "written."

The first step is to prepare the surface or substrate by functionalising it with special molecules. This is where the first nucleotide gets coupled across the surface, forming the first link of a synthetic DNA strand. Next, a technique called maskless photolithography is use: the desired pattern is programmed into a tiny digital micromirror device. This device controls hundreds of thousands of microscopic mirrors, each of which can be tilted individually to project UV light in the correct pattern.

This maskless photolithography technique is especially fun! Imagine being in a house of mirrors with all the lights off. All of a sudden, the lights switch on at the same time the mirrors tilt in different directions, bouncing light every which way. The experience would be disorienting (and maybe a little thrilling).

This UV exposure removes certain light-sensitive caps from specific areas, leaving behind only activated hydroxyl groups (chemical formula: -OH). When scientists flood the surface with DNA nucleotides again, these attach only to the hydroxyl groups at illuminated sites, and that's how the DNA strands start growing.



This process is repeated until an artificial DNA sequence is built at a precise location in the microarray. These are called **DNA zip codes** because they act like a postal address, telling an analyte where they are and how to reach them!

Such DNA traps are perfect for catching other DNA, but what if the molecule we want to detect isn't DNA at all, but a protein? In that case, we call antibodies to action!

SYNTHETIC DNA-GUIDED SELF-ASSEMBLY

It's all about detecting molecules: from our bodies, from other animals or animal products, from the environment... you name it! In the world of diagnostics, we often need to detect a particular set of molecules: proteins.

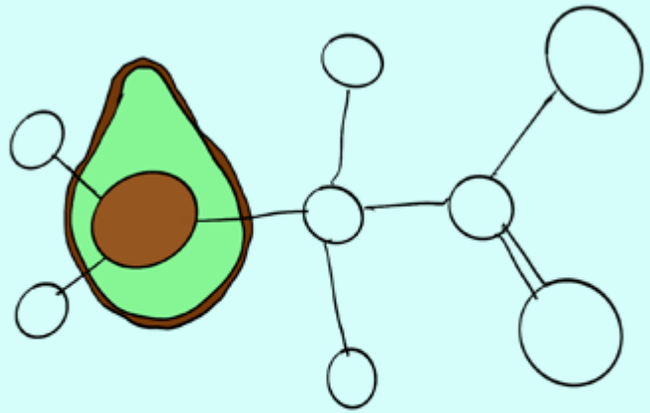
Proteins are the workhorses of biology. Their presence or absence can be a marker for a disease, infection or contamination. The technical challenge is that via **photolithography**, the technique used for DNA synthesis, proteins cannot be detected; it cannot be used to build protein-detectors. So how do we bridge that gap? Well, this is where **antibodies**, the immune system's precision-guided molecules, come in!

To integrate antibodies into a DNA microarray, a sophisticated two-part process is used. Each specific type of antibody is chemically bonded to a unique, pre-designed DNA strand, which functions as a "molecular barcode". Think of each antibody as living on a street with its own mail code. Antibodies that target a cancer protein are sent to street "A," while those that target a viral protein are assigned to street "B." The mail code doesn't change what they do, it just makes them easy to locate and organise.

The microarray chip is then constructed using photolithography. Instead of building DNA sequences to trap a given DNA, an array of "capture probes" (named **zip codes**) is synthesised on the chip's surface (check **photolithography DNA synthesis** for more on this process). These zip codes are the complementary DNA sequences to the barcodes. So, in a precise location on the chip, the sequence that is the perfect inverse match for barcode 'A' is built, and in another location, the match for barcode 'B' is built. This creates a highly organised grid of thousands of unique docking stations, each waiting for its corresponding antibody barcode.

When an antibody solution is introduced in the biosensor, the antibodies disperse and bind to their respective target proteins (if they are present). This mixture is then washed over the microarray. Since DNA strands only pair with their precise complements, each labelled antibody is naturally drawn to the corresponding zip code on the chip's surface. This built-in specificity ensures that antibodies self-assemble exactly where they belong, just as mail arrives safely at the correct address.

As a result, many different DNA-labelled antibodies can organise themselves in parallel, creating a highly ordered functional layer on the chip. This is all guided by the inherent rules of DNA base pairing. The binding events are designed to generate a signal (see **acoustic microresonator**). By reading the coordinates of these signals, the system can precisely identify which antibodies found their targets and often in what quantity. The synthesised DNA isn't catching proteins directly. Instead, it's playing the role of matchmaker and mapmaker, guiding antibodies to their proper places so that the invisible world of proteins can become visible, organized and readable. This is the heart of biosensing.



BIOFUNCTIONALIZATION

If you've never seen this word before, don't worry, you're not alone.

While it may have been born in the early 1980s, it wasn't much in use until the 2000s. Even then, only a relatively small group of materials scientists, nanotechnologists, biomedical engineers, biochemists, tissue engineers and medical researchers used it.

The thing is, the work that these folks have been doing over the past 30 years mean that it *is* a useful term to know, especially as the principles of biofunctionalization have a broad range of applications including in biosensing, tissue regeneration, medical and dental implantation, drug delivery (methods of administering medicines to humans and other animals) and even environmental remediation or clean-up. For example, biofunctionalizing materials such as biochar (a form of charcoal) can make it more efficient at absorbing, degrading, sequestering or otherwise removing harmful pollutants.

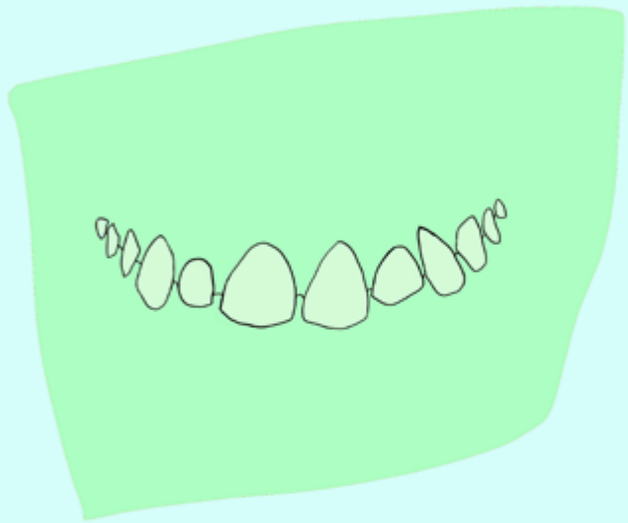
This word has two parts, so let's break it down, starting with the trickier bit, *functionalization*. This mouthful refers to the process of modifying the surface of a material to add new or different properties or capabilities with a specific goal in mind. It's like starting with a car, and getting a custom paint job and installing LED lights to... well... look cool.

Not a great example? Let's add the bio (for biology) and talk about bones then.

Say you have a broken bone and need a titanium implant. Trouble is, titanium is a lot stiffer than bone. This mismatch can cause stress shielding (a form of bone density loss) as the titanium implant absorbs more of the load than the bone itself, ultimately weakening the bone and loosening the implant. Not great, especially for older people who may already have problems with bone density. Researchers have found that making titanium porous can reduce this stiffness mismatch. Once the right structure is achieved using physical and mechanical techniques, the implant can be biofunctionalized. This entails altering its surface so that it interacts better with the biological environment inside the body and reducing some of the health troubles from traditional titanium implants.

In the BIOASSEMBLER project, researchers must biofunctionalize the **sensor array** in order to attach nucleotides (the basic building blocks for DNA and RNA) to the sensor surface using **photolithographic DNA synthesis**. This is an important step for the eventual binding of antibodies to the sensor, which as you may recall will capture the target **analytes**!

Rather than biofunctionalize one single chip at a time, the broader goal of this project was to develop a way to biofunctionalize entire **wafers** at a time, reducing costs and allowing for the mass-production of **bioMEMS** chips. This technology doesn't exist *yet*, but stay tuned and see if you can identify some biofunctionalized materials around you!



THIN FILM DEPOSITION

Have you ever painted the walls of a room? Perhaps you're familiar with the excruciating experience of waiting for paint to dry? Or maybe you skipped the primer, only to be disappointed by layers of flaky paint?

Thin film deposition is a bit like applying coats of paint to a wall, where each layer adds something new and useful. In microfabrication, it is a technique for adding very thin layers of material onto a silicon **wafer**. These layers can change how the surface behaves, for example by making it more conductive, more insulating or more resistant to wear. Thin film deposition is not a one-time step but part of a repeating cycle: first, a thin layer is deposited; then a pattern is defined using **photolithography**; and finally, selected areas are etched away. This cycle of depositing, patterning and etching is repeated many times to build up complex structures layer by layer.

Despite the stiff name, thin film deposition is an exciting area of research and innovation. It offers affordable and effective methods to alter the properties of components used in microengineering (designing and building at the micro-**scale**). Best of all, unlike paint (which adheres to the surface of the wall), thin film deposition allows for the monolithic integration of layers to the integrated chip beneath it! In other words, all the layers — including the integrated circuit and layers of thin film — are fabricated onto the same silicon substrate.

There are two main approaches to thin film deposition: chemical and physical. In chemical approaches, the deposition is reliant on chemical reactions between a heated substrate and the film. In physical approaches, the thin layers of film are deposited physically onto the substrate.

One of the goals of the BIOASSEMBLER consortium was to develop a novel ScAlN* thin film deposition technology — get this — for *depositing **acoustic microresonators** onto the chip that will become the biosensor!*
*ScAlN stands for Scandium-doped Aluminim Nitride.

Buckle your seatbelts, friends, here's how it works:

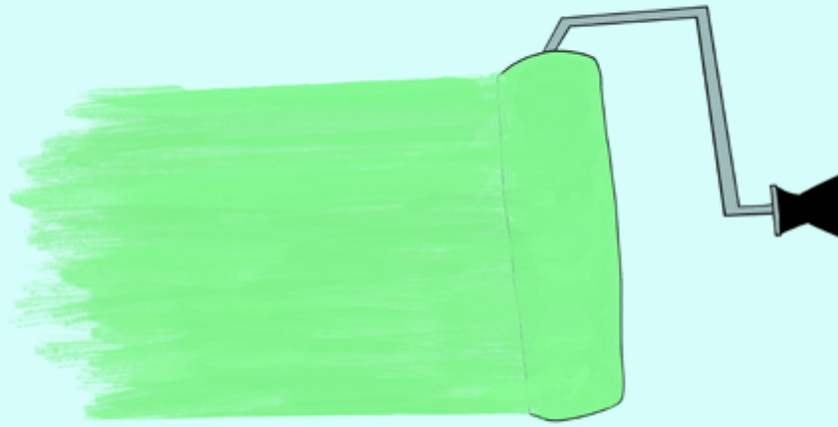
1. Scandium-doped Aluminim Nitride has special properties (if you insist, it has piezoelectric properties) which mean it is durable at high temperatures and more easily generates an electric charge in response to mechanical stress.

2. The folks over at VTT Technical Research Centre in Finland have produced acoustic microresonators using ScAlN thin film.

3. This involves gradually building acoustic microresonators using advanced machines one thin ScAlN layer at a time until the acoustic architecture is complete. (*Psst!* This is all happening on top of the integrated circuit, which is first etched into the wafer).

4. Through this manufacturing process, wafers are produced that contain the acoustic microresonator **sensor arrays**, all integrated into one seamless chip (aka future biosensor).

Presto! Not magic, but microengineering at its finest. But this baby biosensor is not done yet, there are steps to go, including chemically attaching the first nucleotide using **photolithographic DNA synthesis** to create a sequence that will function as a **DNA zip code**.



MICROFLUIDICS

Here's something you might not think about every day: liquids do not act the same on the microscale as they do at the macroscale (*Psst!* Check out **scale** if you haven't already).

When we think of liquids such as water, we might picture meandering streams, rushing rivers or waterfalls pouring down from high above. Or maybe you prefer to imagine drips of coffee filling your morning mug? In either case, gravity, that familiar downward pull to the centre of the earth, ensures that rivers always flow down hills, not up, and that your *xícara*[1] is gingerly filled with espresso.

Yet, at the microscale, liquids can even flow *against gravity*! Yup, you read that right.

Microfluidic engineers can build channels thinner than a piece of paper in which the adhesive forces between the channel walls and the fluid, and the surface tension of miniscule volumes of liquid, are together strong enough to outweigh gravity. This is the same principle that allows water strider insects to walk on water. There's the moon, and then there's the microscale!

Just as water infrastructure engineers build channels, pumps and drainage systems to manage the flow of water on land and through cities, microfluidic engineers design and build microfluidic systems complete with microscopic channels, valves, mixers, pumps and drains that allow tiny volumes of liquid to flow, mix, react and eventually be disposed. All of this action takes place on what's called a microfluidic chip. These are typically either transparent silicon or glass etched using **photolithography**. There are other methods, too, for the construction of micrometre architecture, such as 3D printing.

Think of a microfluidic chip like a miniature circuit, but for fluids instead of electricity. Tiny amounts of liquid move through the microscopic channels and chambers, but all in a flat plane!

Advancements in microfluidic engineering are among the critical innovations that allow for the fabrication of miniaturized diagnostic devices such as biosensors and **lab-on-a-chip** devices at a large scale. Because microfluidic systems are so small, it is relatively easy and cost-effective to make many at the same time, despite the engineering complexity involved in their design.

Beyond biosensors, microfluidic systems can be used for medical diagnostics, single-cell analysis (the study of individual biological blood cells), drug development and testing, disease modelling and more.

Now *that's* something to think about!

1 Xícara, Portuguese for espresso cup, from Nahuatl, *xikáli*, umbilical vessel.

3. Applications

REAL-
-WORLD
BIOSENSING

POINT-OF-NEED, POINT-OF-USE AND POINT-OF-CARE

Developing new technology comes with plenty of jargon, on a bumpy road. Before a new product reaches the real world, there's a lot of testing, refining, and planning to do. This is where the idea of *exploitation* comes in: working not just on the science but also on how to make it count, making concrete use of research results for commercial, societal, or even policy purposes.

Science funding bodies often demand an exploitation plan to ensure that scientific breakthroughs don't just stay on paper but actually make a difference — in clinics, factories, homes, and communities.

To picture this landscape in **biotechnology**, imagine the difference between a fine dining experience and preparing food in your kitchen. Traditional laboratory testing is like a high-end restaurant: precise and specialized, but distant from everyday life. Point-of-care (PoC) is more like a meal delivered to your door: convenient, ready when you need it, and tailored to you. Point-of-use (PoU) feels like cooking your own simple dish, using what's available in your fridge. Point-of-need (PoN) is the most direct of all: like gathering what you need from your surroundings when the moment demands it. These three approaches share one idea: bringing testing and analysis closer to the people and places that need it the most.

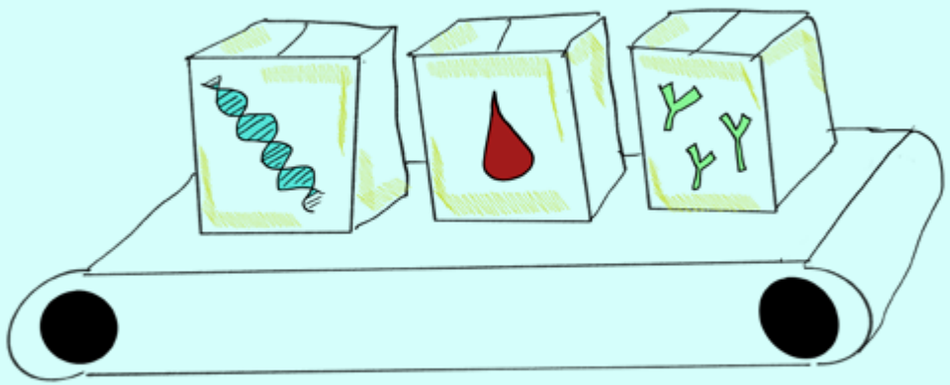
Point-of-care (PoC) technologies are already transforming healthcare. It is not so common today to have to wait days for blood test results to arrive from a central laboratory. Most clinics have small, portable devices with **microfluidic** chips that require a small amount of blood and return results within a few minutes. Then there are self-tests, which anyone can run at home: blood glucose test strips or pregnancy tests. These devices allow any person to easily access a diagnostic, self-monitor their health and make quick, informed decisions.

Point-of-use (PoU) technologies extend this practicality beyond medicine. Different types of sensors (including biosensors) can be built into the systems that sustain our lives: checking water quality, monitoring air inside buildings (hospitals, production facilities, our homes) or keeping industrial production lines safe and efficient. Here, biotechnology blends quietly into the background, making our environments cleaner and our processes smarter without us even noticing.

Point-of-need (PoN) testing brings these worlds together. It's testing that happens anywhere — in the field, in a factory, or at the scene of an emergency — using small, adaptable, low cost devices that deliver answers instantly. Examples include tests for mycotoxins at grain production and storage sites, drug testing the saliva of drivers, or testing milk for antibiotics.

Advances in biotechnology, materials science and digital technology are making these tools smaller, faster and easier to use every day.

The BIOASSEMBLER project contributed to scaling up PoN testing devices developing a new **biofunctionalization** process. The novel biosensor was developed in a real-world example: detecting inflammatory **biomarkers** — key indicators of the body's response to infection and recovery. This proof-of-concept application fits well into the growing PoC market and gives a glimpse into the future of rapid diagnostic testing.



BIOSENSORS FOR HEALTH

There are many projects around the world that aim to build biosensors for human health applications (check out the **health** entry). But creating a single, new biosensor is an incredible challenge. It involves thinking in **ethical**, financial and other dimensions, and it takes a significant amount of time, investment, and research, often carried out through **partnerships** and consortia (singular: **consortium**).

The BIOASSEMBLER project is one such project that aimed to build a multiplex, immuno-based biosensor that uses antibodies to detect biomarkers in liquid biological samples. These include C-reactive protein and Serum amyloid A, two inflammatory markers that, when detected early, can make the difference between a life-saving sepsis diagnosis and a long hospital stay (or worse).

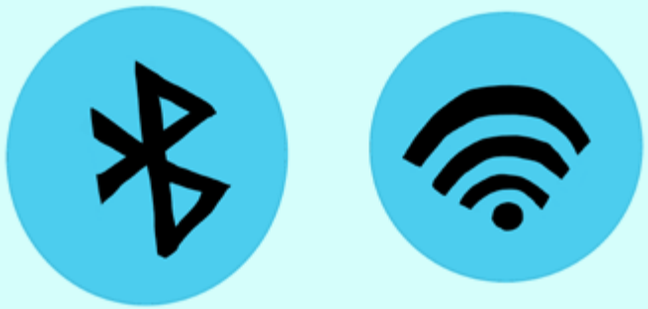
The aim of the BIOASSEMBLER project was to bring this novel technology to the proof-of-concept stage. This means that this biosensor won't be available at the doctor's office quite so soon, but it may enter the pipeline in a short time.

There are many obstacles in the process of creating a biosensor for human health purposes, especially ensuring that the devices are sensitive, selective (detect only what they are designed to detect) and stable (perform consistently). The commercialization of biosensors also requires regulatory compliance to ensure the quality and safety of the biosensor. This, however, creates additional financial and labour burdens for producers. The regulatory load increases with the invasiveness of the biosensor (such as *in vivo*, or implantable biosensors) and the potential risks of device malfunction.

From the side of the patient, user or consumer, there are risks to continuous health monitoring with biosensing technologies, especially in relation to the vast amounts of data that such devices collect and how that data will be stored and ultimately used. Data ownership is also an issue: who owns our personal health data and what approach should be taken in relation to non-anticipated uses of it? For more on this topic, including privacy and surveillance concerns, check out **data and privacy** (and **quantification**).

These ethical and regulatory procedures make it *very* challenging for a new product to arrive on the market. Even in the very best of cases, it can take anywhere between 7 and 10 years for a biosensor to reach commercialization, but there is no guarantee and a biosensor can "fail" at any point.

Failure, of course, might simply be the stepping-stone to success, especially in the world of science and technology where we all stand on the shoulders of giants!



HEALTH

Some of the most incredible applications for biosensors are in human health. These include biosensors for *in vitro* diagnostics (tests done on samples such as blood, saliva or urine), continuous monitoring biosensors, implantable and wearable biosensors, and **point-of-care** biosensors (rapid tests for the home or doctor's office).

Wearable biosensors, in particular, might sound like something straight out of a futuristic world, yet they're already becoming part of our daily lives. They can be integrated into smartwatches, clothing, glasses, skin patches and even one day maybe tattoos. They are especially useful for wellbeing and sports monitoring, such as following the hydration levels of a person. Keep an eye out for high-performance athletes and you might see a vest underneath their jerseys – these are most likely a kind of wearable biosensor. All these biosensors are designed with the same goal: to monitor our physical condition in real time, anywhere and at any moment.

Even more futuristic are implanted biosensors. Yeah, that's right, biosensors can be implanted into our tissue for the continuous monitoring of our health. This development has been driven by the rise of diabetes across the globe, combined with advancements in machine learning and data processing. Today there are many different solutions for monitoring glucose continuously, including by having a sensor implanted in the body, typically around the belly, mid-body or upper arm.

Health biosensors are also available for self-testing. These include test strips for measuring glucose or lactate from a fingerpick, pregnancy tests, as well as tests that detect different biomarkers from urine or saliva. Most people are familiar with these kinds of self-tests following the COVID-19 pandemic, which led to the explosion of rapid tests for coronavirus and other infectious viruses.

The combination of wireless communication with reducing the size of devices to the micro-scale, innovations in **bio-intelligent manufacturing**, **microfluidics**, **DNA synthesis** and more advanced techniques described in this book open the door for countless applications. From more easily managing a chronic disease such as diabetes to the early diagnosis of cardiovascular disease through continuous monitoring, biosensors are very likely to impact many dimensions of human health and healthcare for years to come. Overall, biosensors have the potential to radically reshape the healthcare landscape toward faster diagnostics, expanded research possibilities and personalized, preventative healthcare. At the same time, there are a number of challenges which you can read about in the entry **biosensors for health**.

FOOD

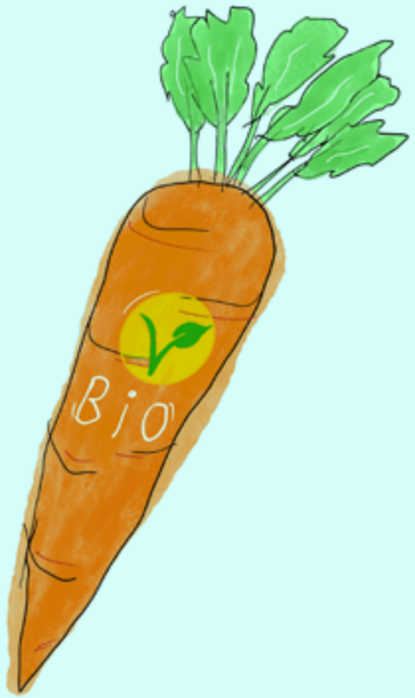
Food has the ability to provide us with the nutrients and energy we need for growth, repair and our overall health, and to create lasting memories. But it must be safe and free from harmful contaminants. After all, no one wants their dinner to come with unwanted pathogens or end in hospital trips! In an increasingly global and complex food supply chain, unfortunately this is a significant challenge. That's where biosensors come in: they can be used to monitor and test food to ensure it is safe for consumption.

Food safety is a huge area that includes the safe production, harvesting, handling and preparation of food at home or in a restaurant. Since many of the foods we consume today come to us via long, international supply chains, food safety also refers to the safety of food during its processing, packaging, transportation, distribution and storage. To make matters more complex, intense competition among producers has given rise to food fraud. Yes... unfortunately, food fraud is prevalent in the European Union in many sectors, like seafood, meat, drinks or honey. And it can take many forms, all for financial gain: food can be mislabelled, diluted, placed in cheap containers and so on. Events like the 2013 scandal of horse meat being sold as beef have stimulated an interest in developing biosensors for food safety.

Biosensors are particularly well suited for monitoring food safety during early stages of production as well as final food products sold in stores. They could be used to detect high levels of antibiotics in milk and meat; dangerous or deadly toxins in bivalves; pesticides and endocrine disruptors; pathogens and viruses; natural toxic fungi in grains, seeds and nuts. Or to determine whether your honey, olive oil and cinnamon have not been mixed with sugar syrups, cheaper vegetable oils or lower quality cinnamon (or worse).

Food-safe paper-based biosensors could also be integrated into food packaging to help consumers tell whether food is safe to eat. More precise than fixed "best by" dates, "active" or "smart" food packaging with built-in biosensors could change colour to indicate whether your chicken is still good, or whether it's really time to throw it away. A major motivation for the introduction of such low cost, simple and easy-to-use **point-of-need** biosensors is to reduce food waste, audit supply chains and protect consumer safety and confidence.

Biosensors offer multinational food corporations and national food authorities a tool to more cost-effectively detect food fraud. **Citizen Science** efforts might also expand the future applications of biosensors for food monitoring. By including small-scale producers and consumers in the food chain at the grassroots level, novel ideas for biosensors could be identified, driven by priorities and concerns distinct from those of large industry players. Additionally, there are solutions to problems of food fraud that do not require investment in more technology, but rather in people who know food.



ENVIRONMENT

What do you think of when you think of the environment? For many, it might be nature that first comes to mind: quiet forests, the windy shore or national parks. But the environment encompasses all of our surroundings: the air we breathe, the water we drink and all that we encounter as we move through our daily lives.

So, when we think about biosensors for the environment, the applications are as far-reaching as those for health and food – and at the same time linked to those areas. The interdependence of the health of humans, other animals and ecosystems has long been recognized, inspiring the concept of "One Health". Might biosensors be a tool for environmental monitoring and the protection of One Health? Could **citizen scientists** make use of these rapid detection tools to investigate their surroundings and hold polluting actors accountable?

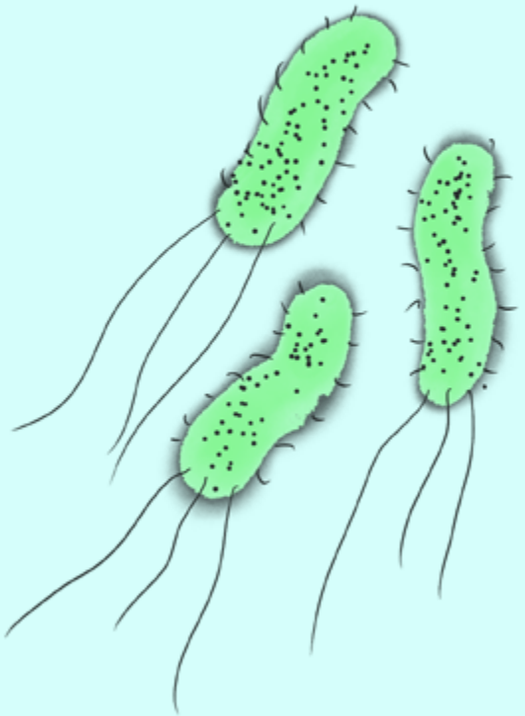
Let's take a look at some of the ideas and innovations:

When it comes to water, biosensors are being developed to detect the presence of heavy metals, chemicals and pathogens (like *E.coli*, a bacteria that can cause severe illness in different animals, including humans). Tools already exist to monitor and detect water contaminants; however, they are typically found in labs. This means that samples must go through a time, labour and cost-intensive process before they can be analysed. The goal with a biosensor is to rapidly and continuously assess the quality of water for human consumption, agricultural use and ecosystem health.

Similarly, biosensors could be used to monitor pollutants in the air such as volatile organic compounds that can come from household cleaners, paints, carpets and cosmetics. They could also be used to monitor carbon monoxide, heavy metals and airborne pathogens like those that cause influenza or tuberculosis. Networks of connected biosensors that continually monitor air quality could be useful in parking garages (where toxic gases accumulate), in urban areas, inside homes and workplaces, and also in dense public places such as hospitals or shopping centres.

There are less human-centric applications for biosensors in the environment, too. After a forest fire, tree biosensors could be used to determine whether a tree is alive or dead and hence whether it should be cut down or not. Implanted (*in vivo*) plant biosensors that continuously monitor glucose levels are not only useful for studying plant metabolism, but may one day be able to monitor the health of plants to determine early stress signs — whether from heat, pollution, or pathogens.

Given that the production, use and disposal of technology ("e-waste") is a significant source of environmental pollution, it is critical that biosensors for environmental monitoring (and all applications) be scrutinized for their **ethical** implications and **sustainability**. The involvement of wide publics in the innovation of biosensors, through commitments to **Open Science** and Citizen Science efforts may also help make sure that these tools are accessible to those who need them and don't further exacerbate digital divides.



FORENSICS

If you believe what you see on TV (not advisable), then Forensics is a glorious, heroic and dare we say, even *sexy* pursuit.

Reality is a far cry from the gilded screen. But that doesn't take away from the importance of Forensic Science as a field in which scientific methods are applied to address legal questions. Forensic scientists use instruments, exams and techniques to identify traces. Bodily fluids (blood, urine, saliva, semen and so on) are often used by forensic scientists to test for DNA. Other substances found at crime scenes, whether liquids or solids, are also tested to determine what they are or what were their sources. Might biosensors offer crime scene technicians another tool to use in their analysis of traces? If biosensors can help people monitor their **health** in life, what are the use-cases for biosensors *post-mortem*?

Despite not being a major focus area for biosensor research (yet), countless are the biosensors that are being innovated to analyse bodily fluids, from blood to sweat and even tears. That's right. Tears. (Picture wearing a pair of glasses with a biosensor built into the nose pad to monitor **biomarkers** in your tears. At least the next time you have a big cry you'll learn something about your health!). This wide range of bodily fluid biosensors could be adapted from the health context to suit the needs of forensic scientists.

But hold up! This is where the **Social Sciences and Humanities** (SSH) come in. It's one thing to build a biosensor with the intention of it having a use-case in forensics. It's another thing entirely for a device to actually be accepted, validated and enrolled into evidence-making processes in a given country. Good tech can fall flat without a broader view of the social, economic, political, cultural and in this case, legal, context in which it might be used.

The BIOASSEMBLER **consortium** made this question a piece of its larger research agenda. And the answer is that we can identify two important points about the application of biosensors in forensic science:

1. New technologies face their own trial before being accepted or standardized (or even rejected) by legal communities, which can take years.

2. Portuguese crime scene technicians are most interested in biosensors that could be used upon arrival at a crime scene (the **point-of-need**) to rapidly identify unknown substances that could be hazardous.

And then we need to consider all the people who would need to accept, validate and approve a biosensor before it could be used in forensics, not to mention questions of cost and the reusability of the device. From national and international institutions to the courts, judges and the legal establishment, there are a lot of people who need to get on board.

Biosensors for forensic science? Absolutely — it's just not so straightforward. The simplest application in this area would be as a point-of-need tool that crime scene technicians could use to rapidly test unknown substances (but not for producing evidence for court).

4. Collaboration

KNOWLEDGE, ETHICS AND SOCIETY

CONSORTIUM

Science is a team sport, but instead of matching uniforms, chants or mascots we put on lab coats, go out to field work and form consortia!

A consortium (plural: consortia) is a group of partners or an association working toward a common goal. They are especially important for how research is organized and funded in the European Union.

Consortia can include universities, public and private research centres, laboratories and businesses or companies. Typically, consortia are formed in response to a research call. In a research call, a funder publicizes a question, a problem or a need. These can take many different forms, but usually invite individuals or teams of researchers to submit project proposals on specific topics. If and when a research proposal is reviewed positively, researchers and institutions may receive funding in the form of a grant to carry out the proposed research.

There are many kinds of funders, including national or local governments, public and private institutions (such as universities or museums), foundations and more. In the European Union, the European Commission is a major funder of research and innovation, including through the Horizon Europe programme.

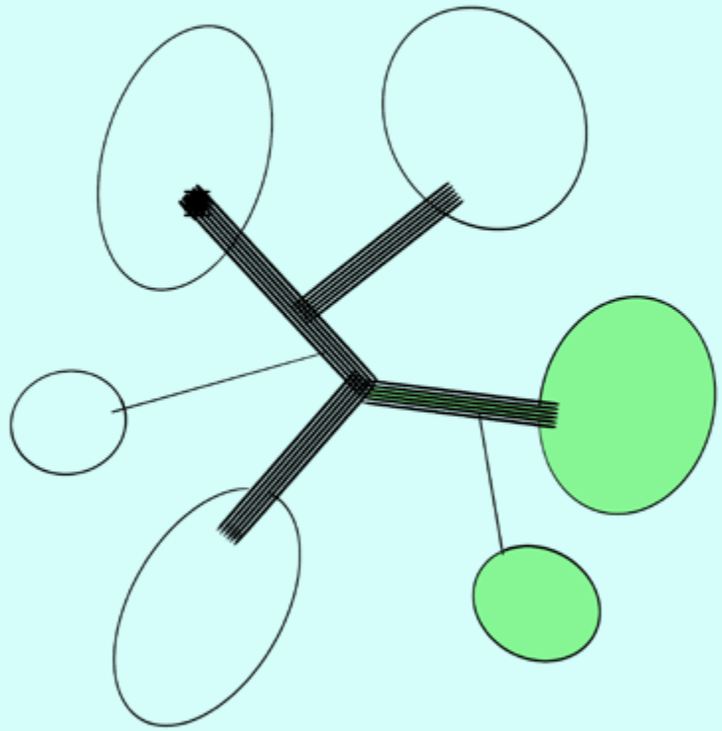
Horizon Europe is particularly committed to fostering collaboration, which is why most funding requires researchers to form consortia. These can be really big (think 36 partners from 19 countries) or much smaller. The BIOASSEMBLER consortium, of which this very book forms a small part, includes six partners from four countries: Finland, Austria, Germany and Portugal.

How do researchers and companies go about forming consortia?

A key factor to consider is the evaluation criteria for each funding line. For instance, having consortium partners spread across Europe (and beyond) can make an application stronger. Other criteria such as gender equality, interdisciplinarity and diverse expertise not only improve the chances of success, but also lead to stronger research and better solutions to complex social and technical challenges.

The truth is, there's no single way to form a consortium. Networking, however, plays an important role. At "matchmaking" or "brokerage" events and academic conferences, researchers meet, share ideas and explore new project opportunities. In-person connections are often complemented by digital networking and by informal word-of-mouth knowledge shared within research communities. Because an important part of research work is **communicating** what you do, whether at conferences or in journals and books — or over coffee!

Ideally, each partner in a consortium brings unique and specialist expertise. Often, consortia are made up of researchers from different disciplines, who come together to create something that is more than the sum of its parts.



SOCIAL SCIENCES AND HUMANITIES (SSH)

If you're wondering what the Social Sciences and Humanities are doing in a book about biosensors and **biotechnology**, you're probably not alone.

Although it may seem an unlikely combination at first, insights and expertise from the Social Sciences and Humanities (SSH) can play an important role in biotechnology and more broadly in science, technology, engineering and mathematics (STEM) innovation. Just like in the BIOASSEMBLER consortium.

Starting from the basics, the Social Sciences and Humanities include an enormous range of fields, areas, experts, practitioners, methods and approaches to analysis and knowledge production. The Social Sciences include economics, sociology, psychology, anthropology, political science, business, education and communication. The Humanities include history, linguistics, philosophy, arts, culture and archaeology. Dig a little deeper, and each one of these areas has many sub-fields and areas. Take "arts", for example, which includes the fine arts, performing arts, literature and a whole lot more. There's a lot of people grouped under SSH, it's a pretty cosy place to be.

So, *what are the SSH doing in a STEM project*?

The sky is the limit!

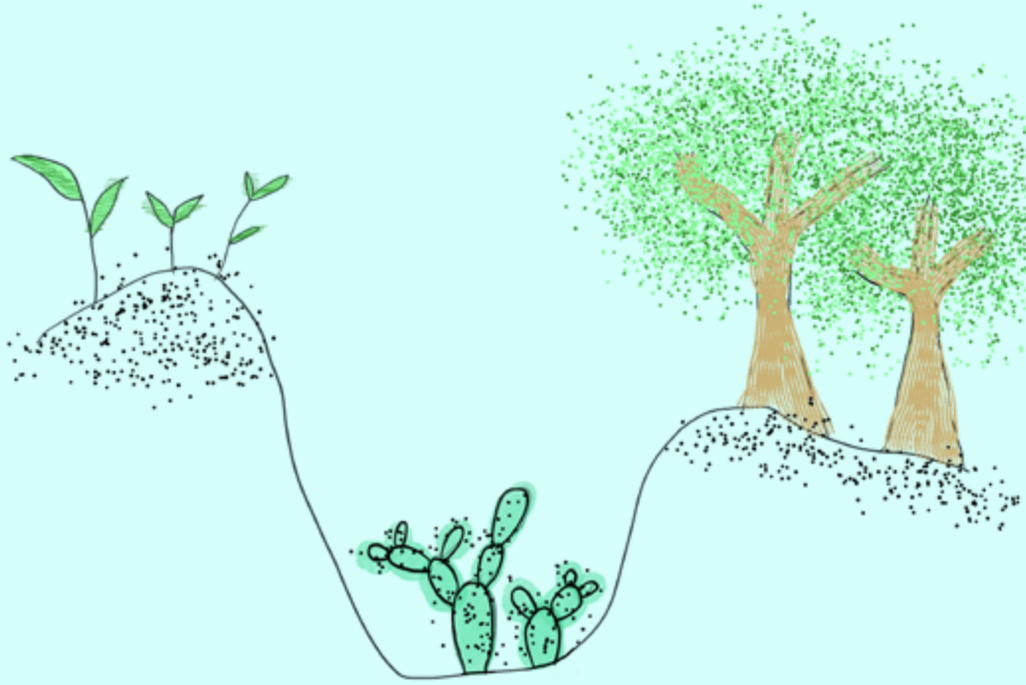
But, let's take it one step at a time.

Scientists, engineers, technologists and mathematicians are really good at conducting scientific research, innovating new technology and contributing incremental and seismic findings about the universe. Social scientists and humanists are likewise really good at understanding and analysing society, politics, economics, culture, language and a whole lot more. Some are also pretty decent at communicating, whether through word, sound, gesture, performance, or image. Not convinced? Just ask a visual sociologist or anthropologist who has dedicated their careers to studying images, values and society!

While probably no one ever asked for an SSH doctor on an airplane, they *did* get a call from some people over in innovation circles about a certain "Valley of Death" that needs bridging. Originally referring to technology companies that struggle to move beyond the start-up phase, the Valley of Death also describes the challenge of moving scientific research and ideas to market, making a social impact and assessing uptake.

When it comes to knowledge sharing and technology, SSH expertise can help bridge this "Valley of Death" by analysing social needs and "readiness"; investigating the impact of existing and emerging technologies; developing engaged **Citizen Science** projects that bring in diverse members of the public to participate in scientific research; communicating the results of research and innovation; ensuring social relevance; offering critical insights on science and technology (see **a critical lens on biotechnology**); providing **ethics** and **bioethics** guidance and much more.

For this reason, since 2020 European Commission-funded research and innovation projects such as the Horizon Europe BIOASSEMBLER project have had to integrate Social Science and Humanities partners into research consortia. The earlier all partners work together, the stronger the proposal becomes and the more impact and social relevance scientific research can have. This is multidisciplinarity at its finest!



SUSTAINABILITY

Much like the term **biotechnology**, sustainability is a broad, commonly used word with competing definitions depending on the context and who's using it. We may think we know what we mean when we talk about sustainability, but this usage might differ from how a neighbour, friend or colleague understands the term.

Breaking it down into "sustain" and "ability", sustainability describes the ability to maintain something in a given state for a long period of time. But sustain what? And in what state? For how long? As a concept, sustainability differs substantially from something like a revolution, which entails the overthrow of a system or social order in favour of something new.

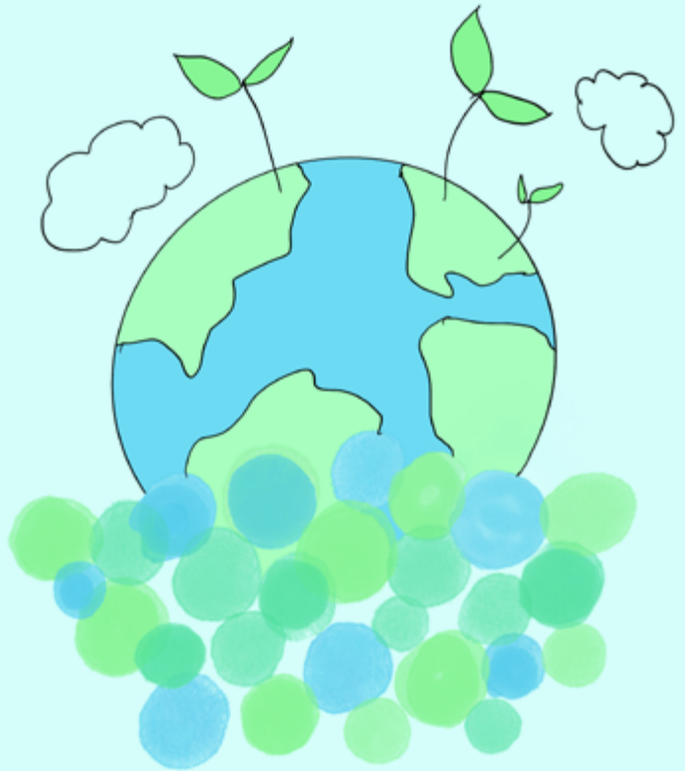
Nowadays, sustainability is most often used in relation to the environment and the economy, though social and cultural dimensions are increasingly considered. Often, sustainability is grounded in the idea of Sustainable Development: meeting the needs of the present without compromising the ability of future generations to meet their own needs (and ideally thrive).

Historically human-centric, there are increasing calls to shift the focus to a more eco-centric view of sustainability that emphasises the interdependence among all species, and between species and their environments. In contrast, linking sustainability to the economy can be contradictory, especially when current regional, national and global economic systems rely on continuous (and even increasing) extraction that threatens the survival of many species.

Things may not look great now, but people around the world are collaborating and agitating to work towards a healthier future. The United Nations' 17 Sustainable Development Goals (SDGs) for 2030 are a well-known example of international goal-setting aimed at protecting life, water, and more. The public's ability to hold governments, institutions and each other accountable will also shape our ability to reach these goals, as distant as they may seem at present.

The European Commission currently funds research through Horizon Europe and other grants to help build toward a more sustainable future. The BIOASSEMBLER project, for example, aimed to transform traditional manufacturing systems with **bio-intelligent** solutions. The idea is to create more resource-efficient, circular and less wasteful production systems through the use of materials at the nano- and micro-scale**.** But innovation brings both benefits and costs: **clean rooms** consume a lot of energy, harsh chemical solvents pollute the air and water, and nanomaterials manufacturing releases invisible particulates that are toxic to organisms. These challenges must be addressed and weighed against the benefits of new technologies.

Critics of sustainability and "green growth" do not think these approaches go far enough to address the climate crisis. Degrowth is a strategy and paradigm that aims to de-link ideas of economic growth from well-being and challenge the premise that anything (other than immortalized cancer **cell lines**) can grow indefinitely. The goal is to reduce production and consumption in equitable, ethical and socially just ways.



ETHICS AND RESEARCH INTEGRITY

What is good? What is bad? How should we live? How do we know right from wrong? How should we form consensus and make decisions? These are just a few of the questions we must ask of ourselves and our world, all of which form the foundation of ethics.

Ethics can be defined in two ways: as a system, code, or set of standards that guide the conduct and morals of a community, and as the study of those systems. Sometimes ethical codes are highly visible. For example, think of traffic signs or religious teachings that guide communities worldwide. Others are unspoken but widely shared, like how to behave in a public park, at work or how to accept gifts and return favours. However, even these unspoken codes are not universal: they are shaped by time, place, culture and community. In all societies, ethical questions, dilemmas and problems arise daily and are constantly changing, often driven by change, including new technologies. For this reason, ethics concern everyone, including researchers, scientists and students.

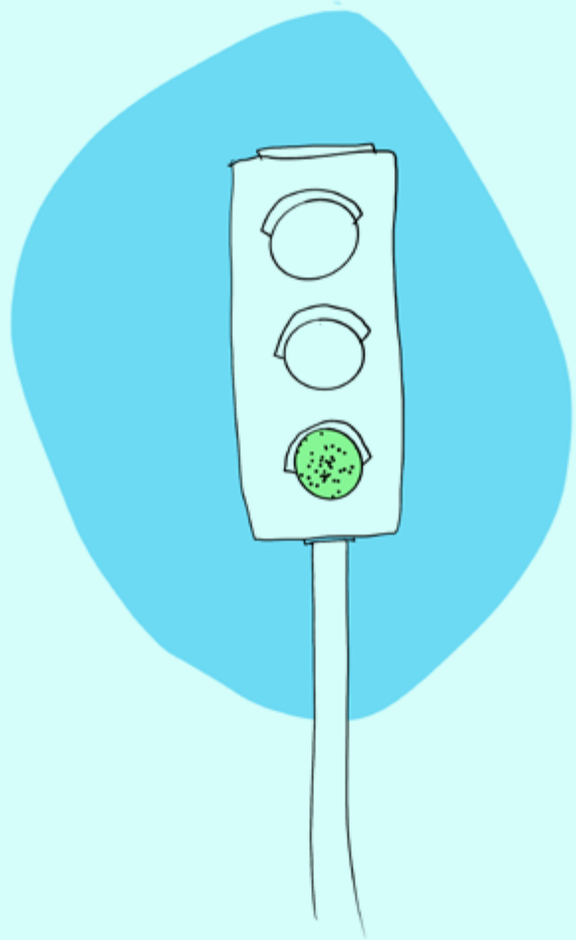
The European Commission, which funds research projects like BIO-ASSEMBLER, understands ethics to include following European and national laws and regulations, and as branch of philosophy that can enhance the quality, integrity and social impact of research, as well as the uptake of its outcomes – whether those concern a biosensor or an exceptionally well-studied strawberry!

Guiding principles include proportionality, the right to privacy, the right to the protection of personal **data**, the right to physical and mental integrity, the right to non-discrimination and the protection of the environment and human health. Proportionality is the idea that the burdens or costs of an action (like doing research) must be balanced against its benefits. Typically, it is the responsibility of researchers to show that the benefits of their work outweigh any harm.

Research integrity is a closely related concept. This refers to adhering to the highest ethical standards, laws, regulations and values such as reliability, honesty, respect and accountability. These should be applied to every stage and dimension of research, including data collection and management; collaboration with colleagues, students, and the public; publication, evaluation and any and all other research activities.

Most research projects require ethics approval from a research ethics committee before they can begin. These committees evaluate research proposals, provide feedback on necessary changes, such as ensuring that researchers obtain informed consent (permission granted with a sufficient understanding of the risks and benefits of participating in research), and advise on the storage of personal data. They also consider environmental, health and safety questions, and can appoint independent ethics advisors or an entire ethics board of experts if necessary!

Contemporary research ethics guidelines, principles and oversight structures emerged in response to historical abuses such as forced sterilization, unethical human experimentation and the administering of drugs without consent. For an example of a historic injustice in scientific practice, see **cell lines**. For more about ethics in biotechnology, see **bioethics**.



BIOETHICS

Bioethics — so, what *is* it?

Well, if you ask three bioethicists to define it, you might get three different answers. The word merges biology + **ethics** to convey a concern with life. Bioethical approaches range from the narrow, such as a patient's end-of-life decisions among family members and involved staff, to the broad, encompassing navigating challenges of genetic technology for the health system.

One way to better understand what bioethics is, is to look at what bioethicists do.

That's right, you can make a whole career out of studying and helping researchers, doctors, policymakers and engineers understand the ethics of their work and deal with thorny ethical questions. Often, bioethicists have backgrounds in life sciences, medicine, public health, law, philosophy and social sciences — or some combination of these depending on their area of focus. Typically, their work is interdisciplinary, combining multiple branches of knowledge.

Bioethicists can work in various places and ways, including hospitals, research institutions or government. They are trained to identify ethical dilemmas that arise in different areas and advise researchers, doctors and patients about ethical issues, help them follow guidelines and provide advice when problems arise. This can be as detailed as ensuring researchers dispose of hazardous chemical solvents correctly. And is especially critical within emerging fields like nanobiotechnology, where new production methods need to be continuously assessed to address potential risks to human and environmental health and safety.

Bioethicists can also serve on ethics committees (reviewing research proposals or clinical trials) and provide training for life sciences researchers and medical professionals. Some bioethicists conduct research on ethics, medicine and technology, engaging in continuous debates and reflection on new ways to think about and address ethical dilemmas.

Bioethics has generally placed great emphasis on bringing ethical deliberation outside academia, empowering citizens and the democratic process. A research group or team developing technologies can include bioethicists even when the work is not directly about applied ethics to guide innovation, anticipate implications and improve compliance and trust.

There are also those who take a broad and long-term view of bioethics. In fact, one of the pioneers of bioethics, the American biochemist Van Rensselaer Potter, presented a very broad definition:

"What we must now face up to is the fact that human ethics cannot be separated from a realistic understanding of ecology in the broadest sense. *Ethical values* cannot be separated from *biological facts*. We are in great need of a Land Ethic, a Wildlife Ethic, a Population Ethic, a Consumption Ethic, an Urban Ethic, an International Ethic, a Geriatric Ethic, and so on. All of these problems call for actions that are based on values *and* biological facts. All of them involve Bioethics, and survival of the total ecosystem is the test of the value system."

While the mainstream, institutionalized form of bioethics focuses on concrete problems in healthcare and biomedical research — often by applying the four principles of autonomy, beneficence, non-maleficence, justice — Potter's broader ecological vision from over 50 years ago appears increasingly visionary.

OPEN SCIENCE

Open Science is like drawing back the curtains on the stage where scientific discoveries take place, making research more accessible and inviting. Forget the idea of research locked away in impenetrable databases or buried in complicated jargon. The proposal is simple: share everything! Well, maybe not *everything*, since **ethical** considerations require protecting some **data**, such as personal data. But the principle is: "as open as possible, as closed as necessary".

In practical terms, Open Science breaks down barriers between scientists, institutions and the public. Researchers make their results and data available in open, free-of-charge journals or repositories for anyone to see, check and use. This means that anyone from curious students and their teachers to entrepreneurs can learn, develop or even challenge the work being done. This transparency increases trust in science and accelerates innovation. When people can explore, question and expand on each other's work, science becomes not only faster, but also more reliable and creative.

Open Science also aims to invite the public into the research process itself. **Citizen Science** initiatives, for example, allow volunteers to work alongside researchers, helping to collect data or push research in new directions. This connection between science and society strengthens mutual understanding and values diverse forms of knowledge. This inclusion is a fundamental characteristic of Open Science aimed at embracing different knowledge systems and promoting equality in the pursuit of discovery.

Beyond changing how research is conducted, Open Science also reshapes how scientific knowledge is shared. Researchers are encouraged to tell their stories in clear language, use creative visuals and share their journeys and findings. By communicating in friendly and engaging ways, they help broaden understandings of what science is and why it matters. The **science communication** and dissemination plan adopted in the BIOASSEMBLER project reflects this broader approach: it's not just about open-access publications and data sharing, but also about reaching schools, using social media platforms or offering workshops and artistic collaborations.

As part of the European Commission's research policy, Open Science policies also drive the definition and implementation of project exploitation plans, seeking to increase the impact of research and ensuring that scientific results become a shared public good beyond the duration of the projects.

The ultimate goal of Open Science is to fuel curiosity and lifelong learning, strengthening science and communities. When more people have access to reliable information, society is better equipped to solve big challenges and discuss them meaningfully. Still, the principle "as open as possible, as closed as necessary" serves an important reminder that some research data and results may need to remain closed, for example to protect a researcher's **Intellectual Property**, but the default should be openness whenever possible.

SCIENCE COMMUNICATION

Have you ever felt like science is an exclusive club with its own language that only members can understand? Well, the whole point of Science Communication is to throw open the doors of that club and invite everyone in. The idea isn't to turn us all into scientists, but to share the wonders, challenges and real-world impact of science in a way we can all grasp and relate to.

Think of it as a translation service. Scientists do their work and then science communicators "translate" their findings into more commonly shared languages. The goal is to make knowledge public and freely available so that others can use it, whether that's to build a new product, shape policy or simply satisfy a bit of curiosity.

In today's research landscape, effective communication is increasingly a mandatory component of most research projects. Funding bodies, such as the European Commission, now regularly require detailed communication and dissemination plans as part of grant applications. This shift reflects a broader understanding that the public investment in science demands public accountability and engagement.

Researchers are often expected to demonstrate how their work will reach beyond academic circles to benefit society, inform policy and inspire future generations. Without a robust communication strategy, projects risk failing to secure funding and missing opportunities to maximise their impact.

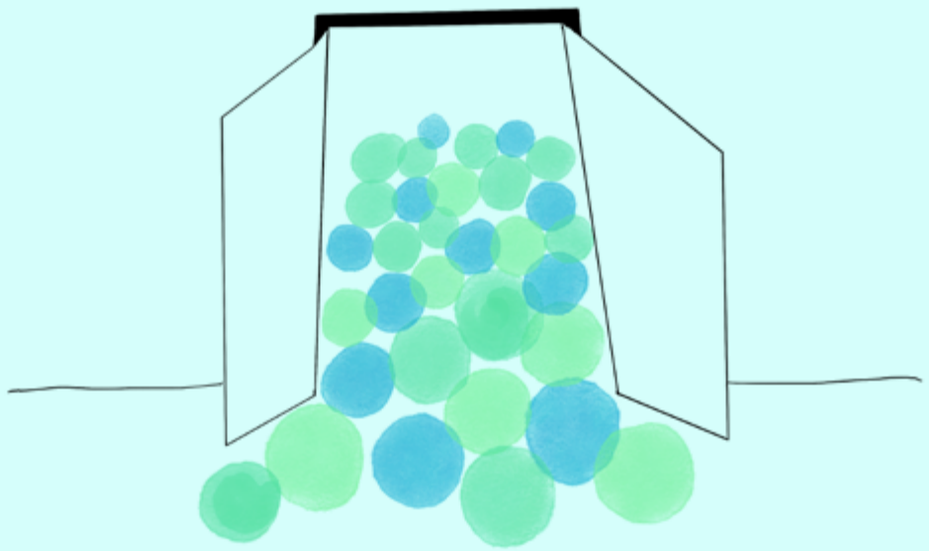
For this to work, projects need a solid plan. One that contemplates not just publishing scientific papers, but also a catchy visual identity, a user-friendly website, and active social media. The (not-so) secret ingredient is to craft clear, straightforward messages that highlight the benefits and impact of the research.

Contemporary Science Communication goes far beyond the (still important) press release. The truth is that communication only becomes a conversation when there is dialogue. Instead of a one-way street where scientists talk and the public listens, the approach now is very much a two-way conversation. It's about actively engaging people, creating a space where experts and citizens can exchange ideas and co-create new knowledge.

One of the most creative and effective ways to do this is through art. Art has a unique power to connect with our emotions and make complex ideas feel simple. Imagine an artist-in-residence at a research centre, collaborating with scientists to create a performance. Or what about a comic book that explains how advanced **biotechnologies** work? And what about this very collection of short illustrated texts you're reading? These artistic approaches help to forge a deeper, more meaningful connection with science.

By blending science and art, communication becomes more inclusive and participatory. It makes complex topics easier to understand, builds trust in innovation and encourages more people to take an active interest in scientific research and its implications. Ultimately, it's about making sure that science isn't something that just happens behind closed doors, but an open and ongoing conversation that everyone can be a part of.

So, hey, now that the doors have been thrown open, what and how would *you* like to communicate?



CITIZEN SCIENCE

Science has often advanced thanks to curious minds beyond the walls of universities and research centres, from early naturalists documenting new species to amateur astronomers mapping the stars. Today, this spirit thrives in the form of a scientific discipline — Citizen Science, a collaborative approach to science that invites the participation of any person (yes, you too!) to work with professional researchers in exploring and understanding the world.

At its core, Citizen Science is public participation in scientific research. Participants might help track bird migrations, monitor air quality or identify signs of disease at a cellular level. Once seen mainly as helpers collecting data, today's citizen scientists often take part in shaping research questions, analysing results and interpreting findings. The message is clear: science isn't confined to specialized spaces or mysterious jargon, it is something anyone can dive into (preferably with enthusiasm, not literally).

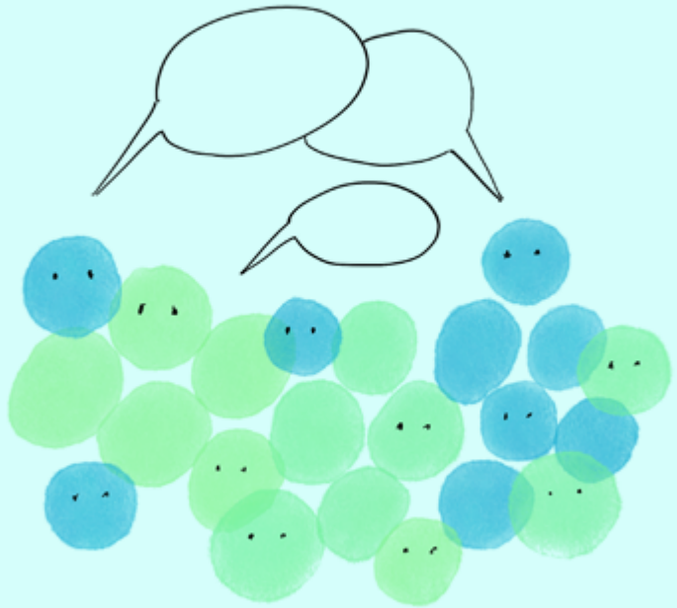
Citizen Science is a vital tool for producing large-scale data and generating fresh insights. Scientists gain valuable information about local and global patterns, while participants gain an insider's view of how scientific knowledge is created. This partnership deepens public understanding of science and strengthens society's ability to tackle pressing challenges like climate change and public health through collective effort.

Although Citizen Science has traditionally flourished in the natural sciences, there is growing interest in extending it to the **Social Sciences and Humanities**. These fields can shed light on the human dimensions of science and technology, including how communities experience, interpret and question them. Projects may explore local histories, cultural practices or social behaviours, reflecting the lived experiences and values of communities and how they relate to past, present and future scientific endeavours.

Engaged citizen social science takes collaboration even further. Here, citizens become co-leaders in research, contributing their values, experiences, and insights from the beginning. The concept moves beyond traditional, top-down methods to embrace co-production and co-learning. Scientists and citizens work side by side to identify problems, develop solutions, and eventually shape policy. And it invites all participants — whether citizens or scientists — to apply a **critical lens** to science itself, examining who produces knowledge, whose voices are heard, and how technology shapes everyday life (for better, worse, or just more complicated gadgets).

This collaborative process can also extend to **Science Communication**. By engaging directly in research, citizens become active contributors in the creation of scientific narratives, helping to design communication strategies and materials that make complex ideas more accessible and relevant. This process transforms communication from a one-way transmission of facts into a two-way dialogue, where diverse voices and perspectives shape how science is understood and discussed.

Citizen Science is about dialogue. It blurs the line between scientist and citizen, transforming research into a shared journey. By working together, we can create richer, more meaningful understandings of the complex challenges we face. And maybe even laugh a little as we uncover the endlessly fascinating, occasionally chaotic and always human story of discovery we all share.



DATA AND PRIVACY

Data — we produce it every time we pick up our phones, it's all around us, decisions are made based on it, supercomputers crunch it, regulators try to protect it, digital sceptics avoid it. But what is it?

Data is typically defined as a set of information about an object or domain of interest, expressed in numbers, images or words. This information, recorded and stored, together make up a database. What is important to remember is that the information must be interpreted for it to become usable or for it to become a (scientific) fact.

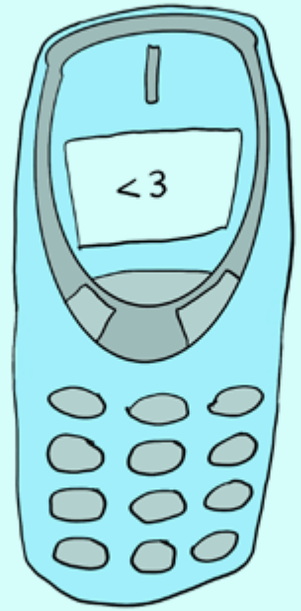
There are many analogue ways to store data (once upon a time we had index cards and filling cabinets), but these have pretty obvious limitations with regard to how much data they can hold. So today most databases are digital.

Alongside the exponential growth of Internet users since the mid-1990s has come the exponential production of data. Nowadays we're talking about Big Data. Zettabytes of data. Data that is so large that traditional data-processing software cannot process it. Social media, sensors, financial transactions (think about every time you tap a card at a shop), all produce data – and most often that data is about the *user* (that's you). All of these data streams flow together to create vast seas of data, much of which is now being interpreted with the use of artificial intelligence (AI) and machine learning. There are benefits that can come from the processing of Big Data, and there are real risks and **ethical** concerns.

Let's consider the example of wearable biosensors and **MEMS sensors** for remote health monitoring. Imagine a person wearing a sensor connected to the Internet that measures heart rate, oxygen levels and sleep. Interpreted by algorithms – potentially even trained on the individual patient – the data collected by these sensors can theoretically be shared with family members, clinicians or even emergency services.

Aside from other challenges (for more, see **health** and **sustainability**), there are also concerns about data privacy and surveillance. At present, wearable devices are not secure, yet they are full of private data including location and health data. In Europe, device manufacturers must comply with the General Data Protection Regulation (GDPR); however, as a legislative framework, the enforcement of GDPR is up to national data protection authorities. In short, just because a device is available to purchase does not mean it is safe to use from a data privacy perspective or immune from cyber-attack (sadly, **antibodies** can't help here).

Many of us like to imagine the pro-society, pro-health applications of biosensors. Yet, they also raise surveillance concerns. For example, in Australia and the United States, it is already the case that some insurance companies offer reduced premiums for people who use such devices. Not only does the company gain a goldmine of information, but personalized plans risk punishing people deemed "unhealthy". Such a burden would fall disproportionately on the chronically ill, the poor, and the most marginalized communities.



PARTNERSHIPS

The category is: best cartoon partnerships. Tom & Jerry. Asterix & Obelix. Tintin & Snowy. Wallace & Gromit. The smurfs? (No, that's more of a collective.) Winnie the Pooh & Piglet. SpongeBob & Patrick. Who would you add? In any case, you get the idea: better together.

We're actually *not* here to talk about cartoons, but another kind of partnership. The kind between universities and industry partners.

These partnerships are increasingly positioned as keys to advance a country's research and innovation (R&I) programs, sometimes also called research and development (R&D). Increasingly, universities are establishing Technology Transfer Offices (see **Knowledge Transfer**), to facilitate the collaboration between researchers and entrepreneurs, and manage the university's **Intellectual Property** (IP). Some of the goals of these partnerships are to find innovative solutions to local, national and global problems; create employment opportunities; increase the impact that university-produced knowledge has on society and drive economic growth.

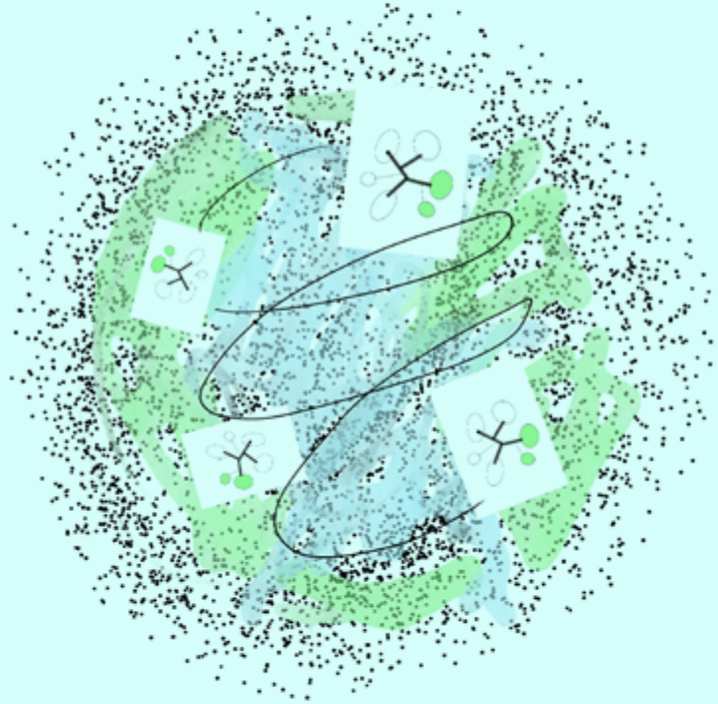
Universities, whether public or private, often contain tens if not hundreds of research centres, laboratories, libraries, working groups and more. They are key sites of knowledge production that play an important role in networks of knowledge sharing, exchange and transfer. Meanwhile, industry partners tend to move more quickly, have expertise in production, marketing and commerce more broadly.

Industry needs ideas, know-how and expertise that sometimes feels "locked" in the university, while universities aim to spread knowledge far and wide, and are increasingly pressured to find alternative revenue streams amid the tightening of public funding for such institutions.

A **consortium** such as BIOASSEMBLER is a kind of partnership. The Horizon Europe research program which funds this project promotes university-industry collaboration in the European Union. This specific consortium includes public universities, research centres and industry partners. By drawing on each other's strengths, knowledge and expertise, the partnership created something new (a proof-of-concept multiplex biosensor), which would have been challenging — if not impossible — to accomplish without such a partnership!

In the international world of biosensing research and innovation, partnerships are forged around the world, but not necessarily evenly. Some countries work closely together, such as Germany, France and England. By contrast, China is the leader in scientific publications about biosensing, but engages in fewer partnerships with non-Chinese institutions relative to other large countries. Brazil and India stand out as important sites of biosensing research in the Global South, but notably there are very few networks that include African institutions.

Biosensor research, design, innovation and commercialisation currently reflect the priorities of the key players, makers, funders and consumers. What biosensors can become and the transformative role that they could play globally could be broadened and strengthened by expanding the community of experts and publics involved in their making!



INTELLECTUAL PROPERTY

Intellectual Property (IP) is a legal term that encompasses several legal regimes including copyright law, patents and trademarks. Unlike most property, which is material (like an apartment, watch or bicycle), Intellectual Property is abstract. It cannot be touched or held in your hand. It most often consists of ideas, information or the creative work resulting from the effort or "genius" of an individual, an institution (such as a research lab) or a company.

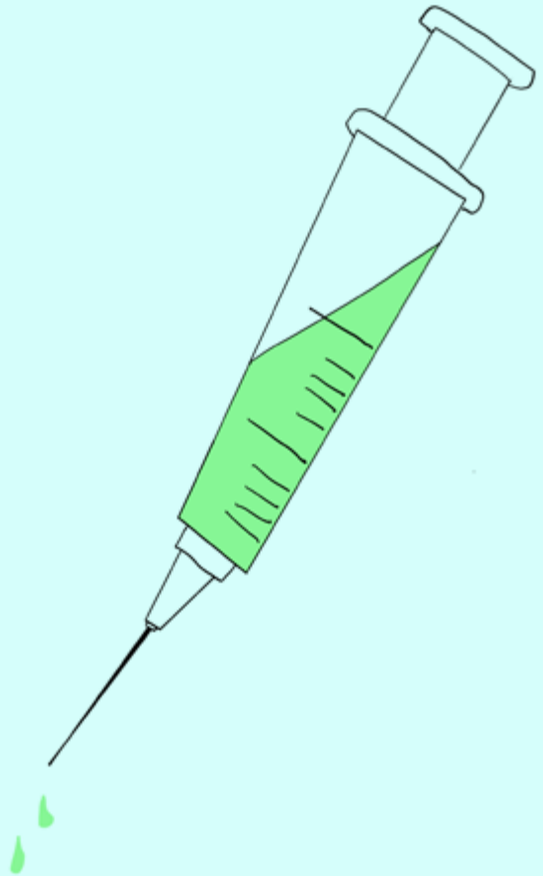
As a concept, Intellectual Property is so vast that it covers an enormous range of creative output. From books and works of art to pharmaceuticals, software and genetically modified organisms, countless are the areas, industries and people that make use of copyright laws, patents and trademarks to claim exclusive ownership of their ideas, discoveries or creations. The ability to claim ownership is dependent on Intellectual Property Rights (IPR), the legal rights that individuals or entities have to claim exclusive use of their creations.

Since it's no good if you come up with, say, a vegan raspberry hazelnut oat milk chocolate bar in France only to have your competitor in Spain sell it for less, there are a range of international conventions, treaties and agreements that govern and attempt to standardize IP laws in Europe and around the world. The United Nations World Intellectual Property Organization (WIPO), founded in 1967, is one such agency that aims to serve "the world's innovators and creators".

There is and has long been a lot of optimism around intellectual property rights and legal regimes as a tool to improve lives, contribute to economic development and incentivize innovation. Indeed, without IP rights and laws, there would be little incentive for investors to fund high-risk research and innovation that results in novel medicines, therapies and vaccines, to name just a few examples.

Sometimes notable Intellectual Property debates arise that draw attention to the many unresolved problems in and produced by this system. For example, during the COVID-19 pandemic in 2020, South Africa and India argued to the World Trade Organization that IP rights to the novel, IP-protected vaccines should be waived for three years to address the severe global inequalities in access to these vaccines. A narrowed compromise was eventually reached, but questions remain about the role pharmaceutical patents play in exacerbating global health inequalities. To be sure, large patent portfolios are linked to profits for pharmaceutical companies, but at what cost and to the exclusion and benefit of whom?

In Europe, research projects funded by the European Commission (EC), including Horizon Europe, are obliged to manage and register their intellectual property rights. This includes notifying the EC about any patents or trademarks, and gaining permission from the EC to share any results, research, or findings that might have commercial value.



KNOWLEDGE TRANSFER

Have you ever conducted research on a subject and then nervously given a presentation in front of other people? Or maybe you've gone on a trip, mapped out the perfect itinerary for visiting all the best snack bars and posted it online?

In essence, these are all ways of transferring knowledge, of knowledge transfer and sharing. The difference between knowledge sharing and knowledge transfer is subtle. Most people who use the term knowledge sharing emphasize the collaborative and social production of knowledge, the context- and time-dependent nature of knowledge and types of knowledge that are not easily transferable. Knowledge Transfer is more applicable to knowledge as an object or property that can be separated from its knower or originator.

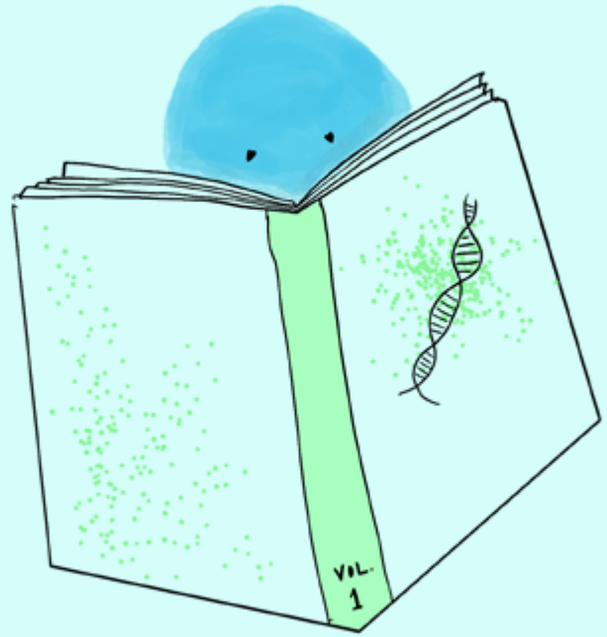
For example, if you memorize the Quran, that knowledge is embodied (living within the self). It can be easily shared through oral recitation. However, the Quran as a book is an example of knowledge that is more readily transferred, given its nature as a written, printed and bound text. In this big old world, there are many forms that knowledge can take.

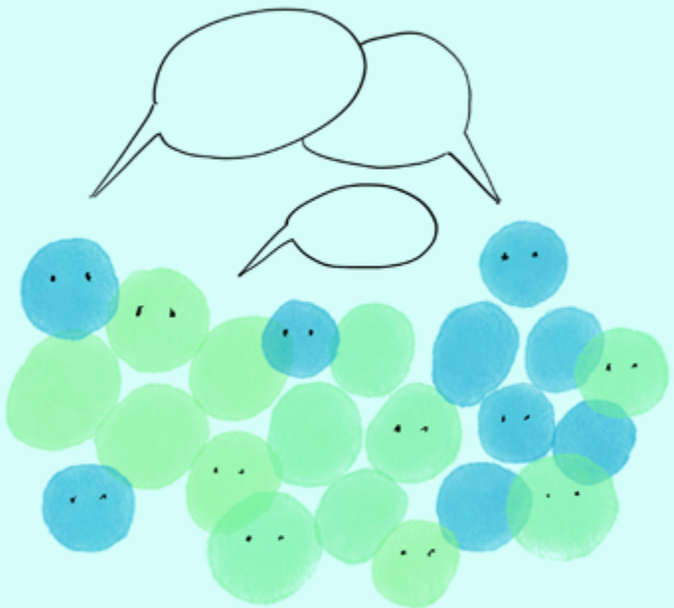
Knowledge Transfer is a term more commonly used in contemporary research, innovation and entrepreneurship circles. Let's look at an example:

Many universities today have what are called Technology Transfer Offices that are responsible for managing the **Intellectual Property** (IP) rights within the university and mediating between researchers and entrepreneurs who might seek to commercialize technology or innovations. Universities increasingly have their own portfolios of patents, the use of which must be negotiated via the Technology Transfer Office, in exchange for money in the form of fees or royalties. The idea behind these offices is to transfer knowledge from the University to "Society" via businesses. Historically, much knowledge has been squirreled away in the ivory tower of scientific corridors or private companies, to the benefit of a relative few. Technology Transfer Offices are envisioned as a mechanism to increase the **partnerships** between universities, researchers and the private sector.

Other channels for Knowledge Transfer include fostering academic entrepreneurship through spin-offs and start-ups, engaging in R&D (research and development) projects commissioned from universities, and providing consultancy work. Further avenues involve the use or rental of university facilities, in-company training of postgraduates and internships, personnel exchanges, and training of company workers by the university. Additionally, joint ventures with universities contribute significantly to broadening the impact of academic expertise.

However, this approach can at times be in tension with calls for **Open Science** aimed at opening up universities, publications and research early and freely as a public good. When research is publicly funded by taxpayers, questions emerge such as: is the university's drive for patents in the public interest, or do they become tools for transferring knowledge (and wealth) further to the private sector? How can strategies for Knowledge Transfer be aligned between stakeholders with different goals, funding sources and deadlines?





It's all about detecting molecules: from our bodies, from other animals or animal products, from the environment... you name it! In the world of diagnostics, we often need to detect a particular set of molecules: proteins.

Across 50 short texts and illustrations, this book invites readers on a journey through the twists and turns of the science behind familiar devices such as pregnancy tests and glucose monitors, and encourages them to think about the ethical and social implications of scientific discovery.