UNIVERSITY OF ZARAGOZA
ROYAL ACADEMY OF ENGINEERING

THE UNIVERSITY IN A HYPER-TECHNOLOGICAL SOCIETY: LESSONS FROM FORTY YEARS OF TEACHING AND RESEARCH

LAST LECTURE GIVEN BY PROFESSOR AND ACADEMICIAN

MANUEL DOBLARÉ

3 JUNE 2026

Universidad Zaragoza

Real Academia de Ingeniería

UNIVERSITY DE ZARAGOZA
ROYAL ACADEMY OF ENGINEERING

THE UNIVERSITY IN A HYPER-TECHNOLOGICAL SOCIETY: LESSONS FROM FORTY YEARS OF TEACHING AND RESEARCH

LAST LECTURE GIVEN BY ROFESSOR AND ACADÉMICIAN

MANUEL DOBLARÉ

ON 3 JUNE 2026

Universidad Zaragoza

REAL ACADEMIA de INGENIERÍA

Edited by the University of Zaragoza

Manuel Doblaré
Printed in Spain

CONTENT

PREFACE

"Often when you think you're at the end of something, you're at the beginning of something else."

Fred Rogers

Before we begin, I want to thank everyone here for making the effort to join me on this very special day, organized by my colleagues and friends. Thank you to them for the idea, the effort, and the affection they've shown me, as well as for making it possible for this event to take place in the most important, most historic, and most beautiful lecture hall of the University to which I've been connected for the last 42 years.

Today I'm not bringing equations or problems to solve. Nor do I intend to talk about Tensor Algebra or Nonlinear Deformable Solid Mechanics, as Fany feared, or about artificial intelligence models, as Elías would have liked, or about sustainability technologies to please my friends at Abengoa Research. After more than forty years of teaching, I thought that, in this final year, I could allow myself something different: to talk not about what I know, nor about what I've done, but about what I've learned. Because, after a lifetime dedicated to teaching, one discovers something one never imagined when starting: that one has been more of a student than a teacher.

Listening to those who have spoken before me, whose words I deeply appreciate, but whose friendship I value even more, I must think I'm an exceptional person. Nothing could be further from the truth. Whatever little or much I have achieved is due to four main reasons, some completely beyond my control. The first and foremost has undoubtedly been the unwavering and unconditional dedication of my wife, Conchi, something I will have the opportunity to acknowledge in the final section. The second has been learning from great teachers, from the earliest stages of my education to the excellence of my mentors, colleagues, and students at university. The third reason, which I have deliberately pursued, has been surrounding myself with people better than myself, as has been demonstrated in the previous contributions. This guarantees professional success and personal growth. Finally, another element that, obviously, has not depended on me, but has been essential, is good fortune. I was fortunate to be born into a family that instilled in me a thirst for learning and the responsibility not to squander the talent I received. I also appreciated being close to wise and generous mentors, and working alongside brilliant colleagues and students, who broadened my horizons.

I vividly remember my first lesson as a professor at the engineering school in Seville where I studied. I was nervous. Much more so than I let on, though less so than I am today. I had my notes carefully prepared, and the problems solved, and I thought, understood. I thought that teaching meant demonstrating that I knew a lot, that I mastered the subject down to its smallest nuances, answering questions without hesitation. Respect, I believed then, stemmed from the confidence with which one filled the blackboard. It took me years to understand that true authority comes from something deeper: from coherence, from intellectual honesty, and from recognizing that one is also learning and therefore can make mistakes.

In the next few minutes, I will try to organize some of what I have learned and share some convictions that I have developed over the years. I don't intend to offer formulas or definitive truths; nor do I intend to engage in a self-indulgent exercise in memory. I simply want to offer an honest reflection on what the university role means to me today. My aim, therefore, is not to solemnly close this chapter, but rather to think together, in a relaxed and informal way, about the role of our institution at this critical moment in history. However, given the scientific nature of this meeting, I cannot completely refrain from presenting a small sample of the latest studies in our group, related to modelling the effects of epigenetic changes on cancer progression. I will, however, try to focus on the less formal aspects, to facilitate understanding for such a diverse audience.

I. A CRITICAL MOMENT FOR HUMANITY

"It has become appallingly obvious that our technology has exceeded our humanity."
Albert Einstein

I.1. A historic fork in the road

It is tempting to interpret each era as exceptional. However, ours possesses features that justify the feeling of being at a historical crossroads. Few generations have experienced transformations as rapid, global, and interconnected as the present. The speed with which our tools, our production systems, our relationships, and our environmental conditions are changing is unprecedented in human experience [1,2]. This is not just a technological shift or a temporary crisis, but a *convergence of transformations*—technological, geopolitical, environmental, and cultural—*that is giving rise to an extraordinary and, at the same time, profoundly unsettling moment.*

The narrative of human history is intrinsically linked to technological advancement. From the controlled use of fire, metals, and printing, to the steam engine and distributed communications, innovations have transformed societies, economies, and cultures. For almost three hundred thousand years, material progress remained largely unchanged. Per capita income, one of the most reliable indicators of our development, remained virtually stagnant, trapped in the Malthusian stagnation [3].

In contrast, over the last three centuries we have witnessed exponential growth in wealth, productivity, and our capacity to transform our environment. As a result, an hour of work in the G7 countries in 2021 produced, on average, 24 times more goods and services than in 1870. This significant increase is essentially linked to the generation of new forms of work, the result of what we now call science, and its widespread implementation stemming from the intensive use of capital. In the Industrial Revolution, science became intertwined with technology, accelerating the process through systematic innovation. This has been, and continues to be, the driving force behind our progress. *To innovate is to imagine what does not yet exist, to transform knowledge into solutions, to take risks, and to dare to introduce changes that improve our daily lives.* Paul Romer said that *ideas are the dark matter of growth* [4].

However, *the current era is characterized not only by change, but also by its pace of evolution and its simultaneous effect on a wide variety of technologies* [5].

Among the most relevant factors driving this acceleration, and first and foremost, is the *speed of data processing and storage*, which provides the fundamental infrastructure for the rest. It is now possible to process and extract information from enormous datasets that were previously unmanageable [6].

Secondly, *ubiquitous connectivity* through the internet and mobile devices accelerates the dissemination of information, innovation, and behavioural changes. Ideas and applications can spread almost instantaneously, generating rapid changes in the emergence, diffusion, and adoption of new technologies, as well as in cultural and social trends [7,8].

Thirdly, *artificial intelligence* (AI) represents a paradigm shift. In just a few years, we have gone from simple tools to systems capable of generating texts, images, medical diagnoses, and making decisions with a level of sophistication that seems like something out of science fiction. AI is radically transforming entire sectors, from medicine to industry, from education to scientific research [9,10].

Figure 1. *Technological convergence, key to the speed of change.*

Fourth, we must mention technological convergence [11]. Fields such as biotechnology, nanotechnology, and neuroscience are increasingly intertwined with information technologies. The synergy between these domains (often referred to as nano-bio-info-cogno convergence) amplifies the complexity and potential impact of their respective advances [12]. Ray Kurzweil coined the "law of accelerating returns," arguing that technological progress in various fields feeds back on itself, leading to potentially exponential growth across all fields [13], which he termed the *Singularity*.

I.2. Towards a hyper-technological society: opportunities, challenges and dangers

The social disruptions stemming from this acceleration are already palpable. *Digital technologies* have transformed communication, community formation, and personal identity itself. Social media platforms connect billions of people, but they also contribute to polarization, misinformation, and a new alienation [14,15]. Concerns about data privacy, surveillance capitalism [16], and the algorithmic bias that permeates crucial decisions are becoming increasingly prominent [17]. Social trust and our very perception of reality are under pressure.

Automation, driven by robotics and AI, is displacing routine cognitive and manual labor, raising concerns about widespread unemployment [18,19], which could escalate dramatically, leading to unsustainable levels of inequality [20, 21].

Figure 2. *A historical fork in the road that may lead to singularity [9].*

Artificial intelligence opens extraordinary opportunities for analysis, innovation, and improvements in health and quality of life, but it also generates enormous risks [22]. Dependence on complex and opaque AI systems can lead to a loss of autonomy and understanding, delegating critical decisions to automated systems with opaque objectives [22, 23]. Advanced AI could enable new forms of autonomous weaponry, thereby leading to an uncontrollable escalation of conflicts [24]. Its combination with facial recognition and ubiquitous surveillance could result in unprecedented social control [25]. The concentration of power in the hands of those who control the technologies is creating global elites that could become unassailable [26]. Finally, the emergence of Artificial General Intelligence raises questions about the role and future of the species itself [27].

The anticipated advances in *quantum computing and communication* will revolutionize fields that rely on complex calculations, such as materials science, climatology, drug discovery, and cryptography [28]. However, it also raises questions about privacy and the conception of time and space [29].

Nanotechnology allows us to envision materials with unique properties in terms of strength, abrasion resistance, or durability; smaller, faster, and more efficient electronic devices; improvements in energy storage; intelligent drug delivery systems; biocompatible conductive materials; and, ultimately, unprecedented control over matter [30]. But it also carries risks such as self-replicating nanorobots or the development of new weapons or undetectable surveillance tools [31].

Advances in *biotechnology, genomics, synthetic biology, and their convergence with AI and nanotechnology* could lead to highly personalized medicine and a radical extension of healthy lifespan [32]. Dario Amodey, founder of Anthropic, believes that AI can accelerate the pace of biotechnology tenfold, with tools like AlphaFold and AlphaProteo [33], coining the phrase "21st Century in a Nutshell," according to which, in 5-10 years, we will advance what biology, and medicine would have achieved in a whole century without them. However, they also introduce serious dangers, such as the accidental or deliberate release of a highly virulent pathogen, which could have consequences far greater than those of natural pandemics [34]. Similarly, there is the possibility that genetic engineering could create a divide between enhanced and non-enhanced humans, fundamentally altering social structures and the notion of equality [35], raising profound ethical questions and prompting a revaluation of what it means to be human [27].

Neuroscience promises to cure neurodegenerative and neuromuscular diseases that have plagued us since time immemorial, as well as to grant us new cognitive abilities, but the potential for psychological and social disruption derived from immersive virtual realities and brain-computer interfaces could alter our identity and free will [36].

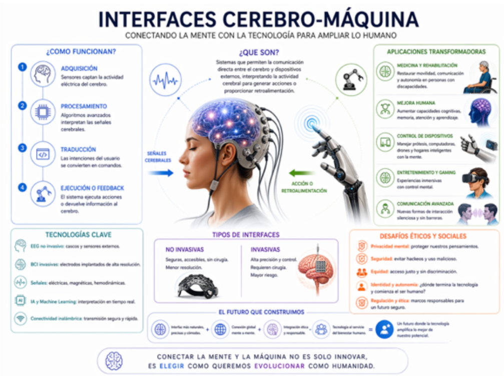

Figure 3. *Brain-machine interfaces, a near future.*

Nuclear fusion, always with a twenty-five-year timeframe, seems to be definitively resolving the enormous problems posed by its efficiency and control. Having safe fusion reactors would guarantee a virtually unlimited supply of clean energy, at a reduced cost, using readily available materials, and with very short radioactive decay times. However, it is essential to ensure that this technology is not limited to a few companies or countries, as happened with fission, and certainly that the possibility of its military use is not extended [37,38].

In conclusion, *the potential benefits of this acceleration are immense*. We can expect solutions to major challenges facing humanity, such as cures for diseases like cancer and Alzheimer's, a considerably longer healthy life expectancy, sustainable energy to reverse climate change, the elimination of hunger and poverty, the expansion of human presence beyond Earth, and the emergence of new forms of creativity, ushering in a new era of unprecedented prosperity and well-being [39]. However, *the associated dangers are equally profound,* including existential threats such as systemic collapses [40], external control of our actions, and even the possibility of total human extinction [41, 42].

If technological transformation redefines our capabilities, *geopolitical evolution* recreates our environment of security and cooperation. The return of high-intensity armed conflicts in regions that seemed stabilized has shattered the illusion of irreversible progress toward peace and integration. The international order that emerged after the second half of the 20th century is subject to profound tensions, if not complete revision. The fragmentation of alliances, rivalry between powers, technology as a factor in geostrategic competition, and the erosion of multilateral organizations generate a climate of uncertainty that directly affects our prosperity [43].

Another major challenge defining our time is *climate change* and, more broadly, *the increasing pressure on the planet's natural systems*. The development model that has enabled the extraordinary progress we enjoy has also generated significant environmental impacts. Unlike geopolitical tensions, which can fluctuate in intensity, the disruption of climate balances is the result of cumulative, long-term processes. These changes remind us that *indefinite growth in a finite system is physically impossible* [44,45]. Engineering and technological development have been a significant part of the problem, but they are also essential for the transition to more sustainable models [46,47]. *We do not have to renounce progress, as some suggest, but we certainly must redefine it.*

Figure 4. *Is climate change unstoppable?*

Although dire predictions about the future can lead to pessimism, this need not necessarily be negative. History shows that periods of greatest uncertainty can also be those of greatest creativity. *We are not facing an inevitable collapse, nor a guaranteed utopia, but rather a range of possibilities.* Whether the crossroads we find ourselves at leans towards progress, the common good, and the improvement of the planet depends on the political decisions, legal frameworks, and strategies we adopt, while passivity in the face of such a profound transformation is possibly the most dangerous path.

To ensure we are on the right track, *new ethical frameworks and structures for global governance and cooperation are needed*, as these technologies do not respect national borders. It is clear that regulating rapidly evolving technologies such as AI security, autonomous weapons, and biosecurity is difficult, and their regulation often lags behind their development and implementation [48], but this does not mean that work is not being done in this area, as it is the only way to prevent abuse by the wealthiest or most powerful, and the confirmation of many of the aforementioned dangers.

Figure 5. *Technology must be constrained by ethics.*

II. THE UNIVERSITY IN A HYPER-TECHNOLOGICAL SOCIETY

In this uncertain and certainly turbulent scenario, in this historical transition, the university must reaffirm its role as a space for reflection, informed debate, and holistic education. The university institution has survived nine centuries because it has been able to adapt without abandoning its essence. As Darwin demonstrated: "*it is not the strongest or most intelligent species that survives, but the one most responsive to changes in its environment.*" [49].

II.1. Teaching in the age of unlimited and ubiquitous information. Tutoring, the invisible legacy

"A teacher is one who makes himself progressively unnecessary."
Thomas Carruthers

One of the most profound changes I have observed throughout my more than forty years of university teaching is not related to curricula, nor to the emergence of new pedagogical methodologies, nor to increasing specialization, but rather to the very nature of knowledge and access to it.

When I began my university studies, information was scarce, and its search was an essential part of learning. Obtaining an article required patience and, sometimes, physical travel and waiting for months. The best universities boasted of their libraries and their access to the most highly regarded scientific journals. But students also learned while searching, since they had to discriminate between sources and organize and synthesize the available knowledge. This search process, seemingly slow and inefficient, nevertheless helped develop critical thinking.

Today, the situation is radically different. *We live in an era characterized by the almost unlimited, immediate, and ubiquitous availability of information*. Never in history has it been possible to consult entire libraries in a matter of seconds, from anywhere on the planet, at any time. Furthermore, we find the information organized in multiple formats and indexed by sophisticated algorithms capable of synthesizing multiple sources of information and generating complete explanations.

Figure 6. *Unlimited, ubiquitous, and instant information.*

However, this extraordinary abundance presents a paradox that directly affects the core of the university's mission: *the accumulation of data does not guarantee deep understanding*. Comprehending a mathematical theory, mastering a physical model, or correctly interpreting an experimental result require processes of intellectual maturation that no tool can replace.

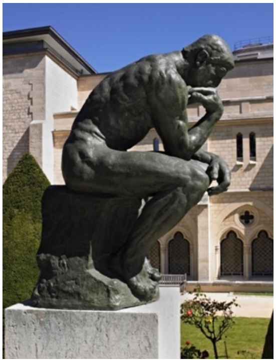

Figure 7. *Rodin's Thinker. We need to teach less content and more thinking skills.*

It is true that artificial intelligence systems allow us to analyse large databases, explore solutions to complex problems, rapidly simulate physical phenomena, and identify patterns invisible to the human mind. But at the same time, they pose obvious risks, as I have already pointed out. If used as a substitute for intellectual effort, they can foster a superficial form of learning. If placed at the service of a critical mind, they enhance it. *In the age of artificial intelligence, the differentiating value lies not in remembering data, which a system can generate automatically, but in understanding its assumptions, its limitations, and its implications*.

The question, therefore, is not whether artificial intelligence should be incorporated into university teaching—something inevitable—but how to do so in a way that strengthens, rather than weakens, students' intellectual development. *Ultimately, the real risk of artificial intelligence is not that machines think too much, but that human beings think too little* [50].

Figure 8. *Teaching in the world of artificial intelligence.*

For centuries, the teacher was the almost exclusive mediator of knowledge. Today, with information readily available everywhere, what role should the teacher play? We must accept that the information students can access far exceeds our own knowledge, so more than a provider of data, the teacher must become a guide. *Education is no longer just about transmitting information, but about teaching students to think, to question, to make mistakes and acknowledge them, in a process of continuous improvement.*

Consequently, universities must change their teaching methods, integrating artificial intelligence to reduce the less creative workload, while simultaneously *fostering the ability to formulate genuinely new questions, to work at the boundaries between disciplines, and to engage in dialogue with other languages—scientific, technological, and humanistic.* Furthermore, it is not enough to train competent professionals; it is necessary to educate citizens capable of thinking critically in a context of constant disruption and understanding the ethical and social implications of their decisions. For this, a vital element that new trends in distance learning seem to overlook is the direct teacher-student relationship. *Mentoring, when practiced with rigor and generosity, is the most significant driver of intellectual and scientific progress.*

Although a professor's academic success is usually measured by quantifiable indicators—publications, projects, citations—these, while undoubtedly necessary, do not capture the human dimension of teaching. A professor's most lasting impact lies in the intellectual and personal transformation of those who have passed through their classrooms. *Articles grow old, theories are revised, models are refined, but people expand, develop, and transmit what they have learned.* This is why, after more than forty years of teaching and research, I have come to a conviction that I would not have formulated in my early years: *the true legacy of a professor, although less visible, is not their articles, nor their projects and works, but their students.* As I pointed out in a recent article with my good friend, Shahzada Ahmad, on the training of researchers, the goal of the mentor should not be to produce obedient followers, but to train scientists committed to their profession, their institution, and society in general, and capable of surpassing their teacher [51].

Figure 9. *A teacher's most important legacy is their students.*

II.2. On merit in the university

"A meritocracy is only as good as the fairness of the competition it oversees."
Chris Hayes

As I have tried to make clear in the preceding pages, a professor's greatest merit lies in the students they have educated, although, as we will see, they also have obligations to contribute to society's body of knowledge through their research, improve the well-being of others, and serve as a moral compass. All of this constitutes a set of obligations that can only be fulfilled with the effort and dedication inherent in the vocation. It is no wonder, then, that society demands a higher level of merit from its professors and, in general, from the entire university community, a level that, nevertheless, is rarely recognized.

In fact, the words "meritocracy" and "elitism" have acquired ambiguous, if not openly pejorative, connotations in contemporary public debate. However, the Royal Spanish Academy Dictionary (DRAE) defines the term "elite" as a select or ruling minority; it does not, therefore, designate a privileged class, nor a closed group of people who come to power for inherited or arbitrary reasons. It refers to those people who stand out for their talent, their effort or their achievements, and who, thanks to that combination of qualities, contribute significantly to the scientific, technological, cultural or economic progress of society.

In societies like ours, which are not inclined to acknowledge that success can stem from effort, dedication, and professional integrity, it is common to attribute success to external factors—chance, birth, personal connections, or even less honourable practices—rather than to sustained work or individual ability. This cultural attitude, deeply ingrained in our country, ultimately creates a social climate unfavourable to recognizing merit and, by extension, to developing a true culture of excellence. However, as a good friend, who is here today, told me, “When you see someone on a mountaintop, don’t assume they were airlifted there by helicopter.”

Figure 18. *A compromise between meritocracy and solidarity.*

Interestingly, this reality is readily accepted in some circles and questioned in others. No one considers it unfair that an exceptional musician has opportunities to hone their craft or that a top athlete receives specific resources to reach their peak performance. In these cases, we clearly understand that talent requires support to unleash its full potential and that this support, far from being an unjustified privilege, represents a collective investment in the success and prestige of society. However, when it comes to scientists, engineers, researchers, or highly qualified professionals, the term "elite" is frequently used as an implicit disqualification. Instead of admiring and trying to emulate those who stand out for their effort and dedication, they tend to be viewed with suspicion.

This attitude reflects a cultural anomaly that ultimately harms society, as it weakens the culture of hard work and reduces the incentives to aspire to high levels of excellence. *The societies that have achieved the highest levels of scientific, technological, and cultural development have been precisely those that have been able to identify, attract, and support their best talent.* In these societies, the existence of intellectual and professional "elites" is not perceived as a threat to social equality, but rather as a necessary condition for collective progress.

However, recognizing merit does not imply abandoning the commitment to equal opportunities. On the contrary, meritocracy taken to its extreme, as Michael Sandel reminds us [52], can lead to attitudes of arrogance and contempt for those who cannot achieve the same goals. This leads to defensive reactions from those who consider themselves undervalued. A healthy meritocracy requires ensuring that all people have access to a quality education and equal opportunities, allowing them to fully develop their abilities, while recognizing and promoting talent wherever it appears, and understanding that failure to achieve success does not necessarily imply a lack of effort or laziness. Talent is distributed much more widely than favourable circumstances. When a society internalizes this dual perspective, the result is a dynamic system in which effort, creativity, and intellectual capacity find real avenues for development, and promotes a well-oiled social elevator, without abandoning or despising those who do not achieve or do not aspire to high goals.

This balance between merit and justice constitutes one of the most delicate challenges for any society. If individual competition is privileged exclusively, without considering starting conditions, there is a risk of perpetuating social inequalities. But if merit is diluted in the name of a misguided notion of equality, the culture of effort that underpins intellectual progress is weakened.

The real danger, therefore, lies not in the existence of elites, but in their arbitrary selection. *A society that neither recognizes nor supports its best talent risks losing scientific, technological, and cultural competitiveness.* Worse still, it can generate power structures based not on merit, but on cronyism, institutional inertia, or organized mediocrity. *At the same time, a society that does not maintain adequate pathways for individual advancement regardless of starting point, or that relies entirely on professional merit for individual success, will face significant social problems.* Those who achieve professional success must not forget that there are multiple factors that have allowed them to reach their goals, not just their talent and effort, and that simply having been able to do so imposes a greater responsibility upon them.

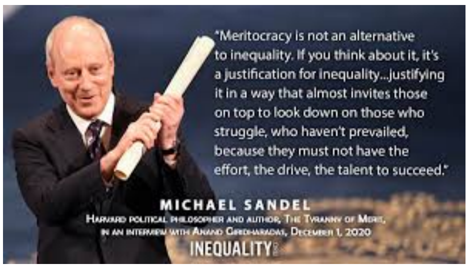

Figure 19. *Michael Sandel and "The tyranny of merit".*

In the university setting, this issue takes on particular importance. Universities are one of the primary mechanisms for selecting and promoting talent in modern societies. The quality of a country's scientific and technological system depends largely on their ability to recognize merit and foster excellence. Therefore, universities must reward effort, intellectual rigor, and genuine contributions to knowledge. Failure to do so creates disincentives, mediocrity, and a loss of institutional trust.

But *the necessary meritocracy in universities must also be responsible.* A truly fair university must strive to ensure that talent can develop regardless of the student's initial social context. This implies the need to offer support mechanisms to those who face greater difficulties, provide personalized guidance, and create real opportunities for each student to reach their full potential. Likewise, those who succeed in this endeavor must be humble and generous with those who do not.

II.3. Research, a fundamental pillar of the university function

"The medicines of today are based upon thousands of years of knowledge accumulated from scientific discovery."

John Vane

The UNESCO report entitled "Science in the Service of Society" [53] includes this paragraph:

"Science is humanity's greatest collective endeavor. It enables us to live longer and better lives, takes care of our health, provides us with medicines that cure diseases and alleviate pain and suffering, helps us obtain water for our basic needs—including food—supplyes energy, and makes life more enjoyable, as it can play a role in sports, music, leisure, and the latest communication technologies. Finally, though no less importantly, science nourishes our spirit."

The recognition of the importance of science and its promotion through research was the origin of the Humboldtian university, championed by Wilhelm von Humboldt at the beginning of the 19th century, as a response to the need to transform higher education into a space where teaching and research were deeply intertwined [54]. In contrast to previous models, focused on the mere transmission of knowledge, this approach argues that knowledge should be actively generated through scientific research and critical thinking, forming individuals capable of questioning, innovating, and contributing to intellectual and social progress, adapting to the changes of an increasingly complex society.

Over the last 100 years, profound changes have occurred in this model, and specifically, in the way research is conducted. Many of these changes have been positive; for example, global investment in scientific research has tripled this century, reaching $2.2 trillion worldwide in 2019. The size and multidisciplinarity of research groups have increased, and there is a progressive integration of public and private teams that jointly tackle enormous projects (Human Genome Project, Brain Project, etc.)[55,56].

Other changes, however, are proving detrimental. In many systems, the fundamental objective of research is being eroded by excessive administration and flawed evaluation and prioritization that stifle its development and limit relevant discoveries. Too often, the university system, and particularly the evaluation schemes and the resulting incentives, lead to confusing means and ends. Articles, impact factors, competitive projects—in short, the means—are quantified. All of these have their function and particular relevance, but none of these indicators, in itself, constitutes the value of research activity. When one understands this, the work acquires meaning. *Research ceases to be a race to gain merits, and with them a more prestigious position, and becomes a responsibility.*

Society funds laboratories, infrastructure, salaries, and training programs because it trusts that the knowledge generated will, directly or indirectly, benefit the collective. This does not mean that all research must have immediate application. This is a shortsighted approach and contrary to my view of science as an intellectual exercise, but it does imply that research must have a horizon of utility. Even when research seems abstract or highly formalized, its ultimate justification lies in the potential improvement of living conditions, including cultural and artistic fulfillment. *Mathematical elegance is valuable, formal coherence indispensable, but the underlying goal of human well-being must always be present.*

I am convinced that *curiosity and responsibility* are two of the most powerful forces for generating new knowledge. Curiosity drives us to understand the world, and thereby to discover and improve; responsibility reminds us that our primary function is to serve society, solving problems that improve our lives, or our understanding of the world or society. *If curiosity explains why we investigate, responsibility explains what we do it for.* The combination of both avoids two opposing pitfalls. On the one hand, it prevents purely utilitarian responses, lacking conceptual depth. On the other, it prevents research from becoming an aesthetic exercise detached from reality.

Figure 10. *Charles Darwin and the Origin of Species: Curiosity as the Basis of Scientific Disruption [49].*

Curiosity is not an intellectual luxury or an academic eccentricity. It is a defining characteristic of our species. From the first attempts to understand the movement of celestial bodies to today's most sophisticated models, the initial impulse has always been the same: Why? This question expresses the refusal to accept the physical, social, intellectual, and artistic world as a set of unexplained facts. But in science, it is not enough to ask questions; it is necessary to do so rigorously, to construct coherent models, to test them against experience, and to subject them to criticism. *Scientific curiosity is disciplined curiosity.*

In fact, the intellectual satisfaction of finding a clearer formulation, a more elegant interpretation of a result, or a more effective or efficient solution constitutes a moment of profound happiness and one of the greatest privileges of academic life. *Having the opportunity to learn and generate knowledge freely is undoubtedly a privilege. However, this prerogative carries with it the obligation to share it, expand upon it, and direct it toward the common good.*

Figure 11. *Research, the basis of innovation and economic development.*

Research is the essential foundation of innovation, and with it, our wealth. However, according to the 2026 Innovation Capabilities Outlook [57], we have entered a period of slowdown in productivity improvement. One of the causes of this slowdown could stem from a lack of new disruptive technologies and from their reduced adoption and/or utilization by industry and society.

In a recent article, Nicholas Bloom asks, "Are ideas harder to find?" [58]. The increase in R&D is insufficient to maintain the pace of progress we have enjoyed. We all talk about Moore's Law for microprocessors, but very little about its inverse, Eroom's Law, which states that, to maintain the pace of discovery, the hours dedicated to the process must be multiplied. In the case of ideas, moreover, increasingly longer learning curves are needed to push the boundaries. For example, we have needed to increase the number of researchers twentyfold in recent decades.

Several other possible factors include the reduction in the risk of funded projects [59], or the growing importance of citations as a measure of scientific success [60]. There are proposals to reverse this situation, which include greater investment in R&D, a larger number of professors and scientists, the application of more technology in the process of generating new discoveries, the elimination of limitations on access to and use of knowledge, and, above all, a clearer strategy to define the direction of growth [61].

II.4. Research in Spain today

"There are no poor countries, only ignorant countries. And the greatest ignorance is not knowing you are ignorant."

Santiago Ramón y Cajal

Research in our country has taken a quantum leap in the last 50 years. During this period, research centers, the number of researchers, dedicated infrastructure and resources, professionalization, and integration into the international environment have all grown significantly. This leads many to argue and boast that Spanish science is at its best and on par with most developed countries, if we normalize by gross domestic product, and, in some areas and indicators, even surpassing them [62].

This optimistic and almost triumphalist view, however, is far from the truth. *The stark reality is that, with a few exceptions, our contribution to the advancement of knowledge is small in relation to our economic importance, and our universities are poorly competitive in research* [63].

If we consider the number of scientific papers published, Spain's current position is good, but if we focus on contributions to the advancement of fundamental knowledge, the situation is considerably worse. Furthermore, Spain's scientific competitiveness has slowed, perhaps due to the mistaken notion that our science was already excellent, which has led to a science policy that, in my opinion and that of many others, is misguided [63].

There are many reasons for this slowdown in our scientific progress, and most of them are well known: i) low levels of public and private investment in R&D; ii) barriers to the mobility of R&D personnel within the public sector and between the public and private sectors; iii) very rigid governance and management; iv) funding based on short-term projects and consultancies, rather than on strategic collaborations or large-scale long-term projects; v) policies that favor dispersion over concentration; vi) insufficient or inadequate policies for attracting and retaining talent; vii) structures, policies, and incentives geared toward incremental rather than disruptive research. Although all of these are important and have been sufficiently described, in the following paragraphs I will focus only on the last four, as, in my experience, they are the least obvious.

Public research funding in Spain, aside from its limited amount, is based almost exclusively on calls for short-term projects (maximum 4 years), of very diverse nature and funding sources. This funding model is used in other countries and seeks to identify useful or groundbreaking ideas that generate measurable results. The problem lies not in the model itself, but in its exclusivity and the way it is applied. The fact that it is the only option forces researchers to dedicate an excessive percentage of their time to writing proposals instead of conducting scientific research. Furthermore, the results of such a large number of applications fluctuate over time, hindering long-term planning and forcing researchers to hire potentially unnecessary collaborators or, alternatively, to terminate their contracts when they are more useful. *As I have repeatedly argued, funding is necessary, but continuity is far more so.*

Secondly, maintaining the cohesion of large research groups requires a monumental and constant effort. It is much easier to work with limited objectives and requirements than to join larger companies, where we depend on others, and individual recognition and visibility are lower. Moreover, a researcher's evaluation, and therefore their ability to secure funding and recognition, depends, among other indicators, on having participated in project management. This forces junior researchers to become independent as soon as possible to be recognized as principal investigators. This fact, combined with the limited mobility of researchers in Spain, leads to a premature fragmentation of research groups, favouring the desirable advancement of individuals. However, as we will discuss later, collaboration within and with large groups is essential to address significant challenges and avoid missing opportunities. Unfortunately, *Spanish universities lack the strategies and resources to create and maintain large-scale collaborative initiatives.* Thus, to use the analogy of my good friend José Domínguez, "too often, the university becomes a ship where skilled and dedicated rowers row in different directions, without any control or direction, leading to stagnation."

Thirdly, there is the attraction of talent. *There is no better investment for an institution or a country than attracting outstanding researchers.* This has been repeatedly confirmed in numerous reports, which demonstrate that new talent pays for itself in very short periods and offers enormous returns in the medium term [64]. Fortunately, this is one of the areas where we have improved the most in Spain. Programs such as Ramón y Cajal, Miguel Servet, ICREA, IKERBASQUE, ATRAE, and many other smaller regional programs are irreversibly changing the research landscape in Spain. Even so, and considering their benefits, it is difficult to understand why they are not even more numerous and geographically widespread.

Finally, perhaps the most damaging policy affecting research in Spain concerns the evaluation of research outputs, and consequently, the promotion and incentives for researchers. This evaluation is based primarily on the number of articles published, the prestige of the journals in which they are published, and the total number of citations (or similar indicators).

However, numerous studies scientifically demonstrate that these indicators can be useful for evaluating, in aggregate, a country or a large institution (e.g., a university), but not an individual researcher. Furthermore, none of these indicators measures disruptive research, only incremental research. If we add to this the fact that excessive project risk is often penalized (unjustifiably, the EXPLORA program was discontinued a few years ago), the consequence is obvious: researchers tend to avoid the risk of publishing infrequently, and thus losing incentives and opportunities, in exchange for a higher probability of making highly relevant contributions. Of course, research on important topics always carries the risk of being wrong, but as Peter Medawar, Nobel laureate in Physiology or Medicine in 1960 for his work in immunology, comments in one of his books: "*Anyone who wants to make important discoveries must study important problems.*" [65]

The result is that *this approach to science has led in recent decades to an overemphasis on incremental developments and applications, to the detriment of exploring new ideas, disruptive results*, and, consequently, the P_{500} ratio between the publications in the top 500 most cited in each field and year, and the total number of publications [63, 66]. This situation affects many other countries, but scientifically peripheral countries like ours suffer the most.

Table 1 shows that only five countries (USA, Switzerland, Germany, UK, and the Netherlands) are at the centre of global knowledge production ($P_{500} > 0.09$ and $P_{5000} > 1$), with another core group of countries nearby (Australia, Singapore, Denmark, etc.), while the vast majority are far behind. Japan and China are exceptional cases, as the former has a very strong applied sector that inflates total publications, distorting the ratio, and the latter is rapidly approaching the centre [66]. Spain is far behind in both cases, with a P_{500} ratio almost four times lower than Portugal's, which again supports the assertion that we produce an excessive number of publications of little value.

Table 1. *Ratio between the number of publications ranked between the 5000 and 500 most cited in the world and the total number of publications in the fields of physics, chemistry and engineering in the period 2008-2017 and citations in the period 2018-2020 (x1000) (Note: Publications in collaboration with other countries have not been counted) [62]*

País	5000	País	500
Estados Unidos	1,60	Suiza	0,217
Suiza	1,30	Estados Unidos	0,163
Alemania	1,24	Australia	0,140

Tabla 2. Continuación

País	5000	País	500
Singapur	1,14	Reino Unido	0,124
Reino Unido	1,08	Países Bajos	0,098
Países Bajos	0,81	Alemania	0,098
Australia	0,74	Singapur	0,073
Nueva Zelanda	0,70	Austria	0,054
Canadá	0,59	Dinamarca	0,054
Dinamarca	0,59	Francia	0,043
Bélgica	0,48	Portugal	0,041
Israel	0,46	Japón	0,032
Suecia	0,45	Canadá	0,028
Austria	0,43	Italia	0,026
Francia	0,38	República de Corea	0,025
China	0,38	China	0,015
Japón	0,33	Brasil	0,012
Noruega	0,32	España	0,009
Finlandia	0,30	Nueva Zelanda	0
España	0,26	Bélgica	0

It is essential to change this trend. While continuing to support incremental research, since disruptive research is impossible without it, we must simultaneously foster higher-risk research. It's not about funding "excellence," as some believe, if excellence is measured by the same parameters. We only need to look at countries of similar size to ours, such as Switzerland or the Netherlands, to see how they operate.

II.5. The University as an agent of social development

"Higher education is a public good and a strategic asset for sustainable development."
UNESCO

From its medieval origins, the university has been linked to the society that sustains it, but this relationship has acquired a far greater intensity and complexity than in the past. *The extraordinary growth of scientific knowledge, technological acceleration, and the increasing interdependence between science, technology, economics, and politics have transformed the university into a central actor in social development.*

Knowledge has ceased to be merely a cultural asset and has become one of the main drivers of economic progress and collective well-being. *Scientific research transforms resources into knowledge through the talent and creativity of researchers; innovation, in turn, transforms that knowledge into wealth, new technologies, and social value.*

The university's contribution to well-being, in addition to the generation and transmission of knowledge, takes other forms, which can be grouped into four main functions: the transfer of technology and knowledge to the productive system, the training of professionals capable of generating innovation and progress, the dissemination of scientific and cultural knowledge that integrates it into society, and its role as a civic conscience.

II.5.1. Technology Transfer

From the Industrial Revolution to current digital technologies, scientific development has profoundly transformed the material conditions of human life, contributing decisively to poverty reduction, improved health and life expectancy, and the expansion of well-being in vast regions of the world. *Scientific and technological progress has thus proven to be one of the most determining factors in economic growth and the competitiveness of nations.*

However, the relationship between research and innovation is not automatic; the former is a necessary but not sufficient condition for the latter. *For knowledge to be transformed into value, a complex ecosystem is needed, involving companies, universities and research centres, public institutions, investors, and entrepreneurs.*

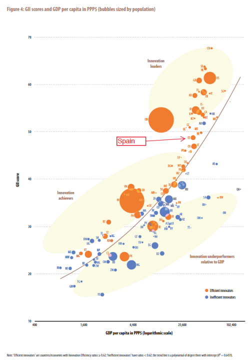

Figure 12. *Relationship between GDP and the global innovation index of different countries [69].*

Consequently, all countries attempt to foster innovation in their companies and institutions through actions such as strengthening innovation agents and their interactions, supporting other actors in the ecosystem (e.g., venture capital and seed capital), providing resources (personnel, infrastructure, etc.), and supporting complementary policies such as education and dissemination, taxation, and talent attraction, among others.

In Spain, *this interaction has historically been, and continues to be, highly imperfect.* It is common to speak of the Spanish paradox as an intensification of the well-documented European paradox, according to which, despite the quality of our scientific research, the system's capacity to generate technological innovation remains limited [60]. However, as I have tried to establish earlier, this widespread diagnosis that Spain is inefficient only in knowledge transfer lacks empirical support. Public research in Spain is also inefficient in generating the knowledge that underpins radical innovations.

In the 2025 Global Innovation Index report, Spain ranked 29th among all countries, well below its potential in terms of GDP and supposed scientific strength [69]. This position reflects some worrying symptoms of the Spanish economic system, most of which are well known: i) low productivity; ii) low wages; iii) high unemployment; iv) low educational attainment; v) low output in technological production (patents, high-tech goods and exports, etc.); vi) few ecosystems with companies, universities, and technology centres; vii) a scarcity of public-private co-investment policies. This is because, in addition to the weaknesses of the knowledge generation system, the Spanish Innovation System exhibits other shortcomings.

Within companies: i) a weak innovation culture in some productive sectors; ii) small average company size; iii) limited business investment in research; iv) low levels of employment in R&D&I and technological development; v) a small number of companies that systematically participate in R&D&I; vi) the absence or deficiencies in innovation strategies and intellectual property protection; vii) the low professionalism of R&D&I project managers; viii) a low level of digitalization and internationalization; ix) inefficient management of internal knowledge and a low capacity for absorbing external knowledge.

In the administration and the socioeconomic environment: i) deficient education at all levels, which does not meet the needs of businesses; ii) risk aversion and, consequently, a low rate of creation of technology-based companies; iii) limited social recognition of research and innovation; iv) low priority given to R&D&I; v) poor coordination with the European Union and among autonomous communities; vi) difficulties in promoting emerging technologies; viii) a lack of flexible financing instruments for technology-based companies; viiii) very rigid and bureaucratic management..

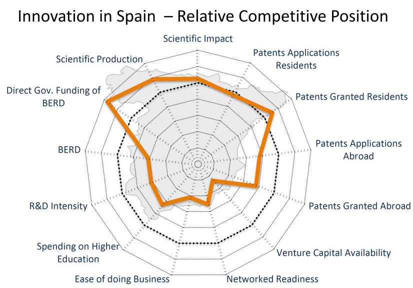

Figure 13. *Strengths and weaknesses of innovation in Spain [69].*

To overcome all these difficulties and thereby improve the long-term quality of life, *Spain needs a comprehensive political and social agreement to change its educational, research, and production model, establishing the creation of valuable knowledge, the leveraging of individual and organizational talent, environmental sustainability, and continuous innovation as the main drivers of the country's new growth model.*

Although, in recent decades, there has been a substantial increase in awareness that the knowledge generated must find effective ways to translate into economic and social value, *universities still need to learn to identify their applicable research potential*, adequately protect intellectual property when necessary, and establish strategic alliances with companies and institutions capable of transforming the knowledge generated into concrete applications, and, finally, promote the creation of new businesses.

It is also necessary for the business sector to incorporate innovation as a central part of its competitive strategy. Companies that do not invest in knowledge are condemned to compete solely on cost, a strategy that is hardly sustainable in a global economy based on the added value of knowledge.

Throughout my academic career, I have had the opportunity to participate in various initiatives to strengthen this interaction between universities and society. I am therefore aware of its difficulty, but also that it is possible. The creation of interdisciplinary research institutes, the promotion of projects with companies, the fostering of technological spin-offs from universities, the creation of a research company from scratch within a multinational conglomerate, or the promotion of a complete innovation ecosystem with university, research and technology centres, business incubators and the government, are some examples in which I have participated directly, demonstrating that, indeed, the university can contribute actively and decisively to the direct generation and promotion of innovation.

II.5.2. Training the engineers of the future

While knowledge transfer is the most visible form of interaction between universities and society, the training of professionals responsible for its implementation likely represents their most profound and lasting contribution. Technologies change, companies emerge and disappear, but university graduates continue to act for decades as vectors of knowledge, innovation, and social responsibility. Ultimately, *the impact of an academic institution is measured less by the number of published articles or registered patents than by the intellectual and human quality of the generations that have passed through its classrooms, and, in particular, by their contribution to improving social conditions.*

Figure 14. *The engineer of the future?*

In the specific case of engineering, this responsibility takes on a special dimension. The world we inhabit, shaped, enabled, and sustained largely by technology, depends decisively on engineers. They translate scientific possibilities into tangible reality. As I often tell my students: *an engineer is someone capable of providing implementable solutions to problems with incomplete information, and without the time and money to achieve an optimal solution.*

To work in this way, the engineers of the future will need to expand and combine aspects such as:

- A solid scientific foundation and rigorous analytical and quantitative skills that enable them to understand complex phenomena, predict and optimize using science, experience, and data, critically evaluate new technologies, and adapt to unforeseen problems.
- Creativity and innovative capacity to address future challenges and drive progress, creating innovative solutions under constraints of resources, time, ethics, and regulations.
- Systems thinking that empowers them to view problems holistically, understanding how different components interact within a system.
- The ability and willingness to think, communicate, and work effectively across diverse fields, collaborating not only with engineers from other specialties, but also with scientists, economists, lawyers, sociologists, policymakers, ethicists, and end users.
- A problem-solving approach to ensure that the systems they design function reliably, efficiently, and safely.
- An ethical responsibility that prioritizes safety, health, public welfare, and environmental stewardship.

All of this requires a fundamental rethinking of engineering programs, how we use pedagogical methods, and how we assess learning.

II.5.3. The Dissemination of Science and the Humanities

Another area of the relationship between university and society, which, although less visible than education, research, or technology transfer, is equally essential for the functioning of an advanced society, is the dissemination of scientific and humanistic knowledge.

Scientific knowledge cannot remain confined to laboratories or specialized journals. It must be integrated into general culture, contributing to the formation of citizens capable of understanding the world in which they live and of participating in an informed manner in the public debates that affect their future. Scientific dissemination fulfills precisely this function. *Disseminating knowledge means building bridges between specialized knowledge and general culture, between academic research and the everyday experience of citizens.*

In a democratic society, citizens must participate in the decision-making processes that affect the collective future. But this participation can only be truly free and responsible if there is a sufficient level of scientific literacy. *Science communication is therefore not a secondary or merely ornamental activity; it constitutes an essential component of the functioning of a modern democracy.*

In this sense, science communication is one of the noblest forms of interaction between universities and society. It does not produce direct economic value, but it contributes to something equally important: *the construction of an educated, critical society capable of understanding the meaning of scientific and technological advances.*

This task is especially important in an era characterized by the growing influence of science and technology in all areas of social life. Political decisions related to energy, public health, climate change, or artificial intelligence require a sufficient understanding of scientific concepts that, until a few decades ago, remained restricted to academic circles.

At the same time, science communication plays an essential role in the training of new generations of scientists and engineers. Many researchers have discovered their vocation through popular science books, public lectures, or educational programs that sparked their intellectual curiosity at an early age.

Nor should we forget that science communication should not be limited to science and technology. The humanities play an equally essential role in building a critical and reflective culture. History, philosophy, literature, and art provide interpretive frameworks that allow us to understand the cultural, social, and ethical significance of scientific advances, in addition to contributing to humanity's intellectual heritage.

The traditional separation between the sciences and the humanities, largely inherited from the academic structures of the Middle Ages, is increasingly artificial in the contemporary world. The great challenges of our time—climate change, artificial intelligence, biotechnology, and energy sustainability—cannot be understood solely from a technical perspective. As Charles P. Snow reminds us in his essay on "*The Two Cultures*" [70], the distorted image that the sciences and the humanities then had (and, unfortunately, still have) of each other is destructive, and their reunification is a necessity in both an intellectual and a practical sense.

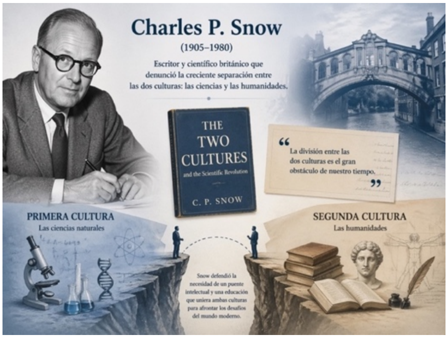

Figure 15. *C.P. Snow and "The two cultures".*

II.5.4. The University as a Critical Reference Point

The university is not merely a space where natural phenomena are investigated, theories are developed, qualified professionals are trained, or innovations and improvements are promoted. Throughout their existence, universities have undergone profound transformations that have changed their disciplines, pedagogical methods, organizational structures, and even their relationship with political and economic power. However, they have maintained a recognizable identity, faithful to the idea that knowledge must be cultivated with rigor, independence, and responsibility, and have decisively contributed to shaping the cultural and ethical landscape of the societies in which they are embedded.

University institutions not only produce knowledge; they also contribute to developing critical thinking, responsibility, and awareness in those who will assume scientific, technical, or political responsibilities in the future. It is, therefore, also a moral institution in the deepest sense of the term, a place where the values that make possible a collective life based on intellectual freedom, the pursuit of truth, and responsibility toward society are cultivated and transmitted. Universities have also played an essential role as spaces for independent reflection, where dominant ideas have been questioned and well-founded arguments have been developed that have subsequently influenced the evolution of societies.

This ethical dimension of the university acquires particular importance in our time, characterized by profound technological, geopolitical, and cultural transformations and by moral relativism. However, in recent decades, the university has tended to withdraw into itself, concentrating much of its energy on internal dynamics of evaluation, funding, and institutional competition and positioning. *For too long, the university has been* *reluctant to intervene clearly in certain public debates,* which has allowed the space of social discussion to be occupied too often by discourses lacking scientific rigor or intellectual responsibility. *This withdrawal has contributed to weakening its role as a critical reference point in public debate.*

It cannot be denied that the university is composed of a plurality of opinions and perspectives. This diversity is precisely one of its greatest strengths, but it should not lead to a paralyzing neutrality on fundamental issues. There are principles that cannot be subject to short-term negotiation; among them, the defense of freedom, the pursuit of objective truth, and respect for human rights.

Figure 17. *Pseudoscientific charlatans.*

The proliferation of pseudoscientists, self-appointed pundits, and social media professionals—not all of them, of course—is, in part, a consequence of this void. In the absence of a clear and accessible academic voice, simplistic or blatantly erroneous interpretations of complex phenomena proliferate, directly affecting social well-being. *Recovering the critical function of the university does not imply turning it into a partisan political actor* *but rather remembering that knowledge has a public responsibility that cannot be ignored.*

Because of the uncertainty generated by all the above, *we are witnessing a crisis of confidence in institutions*. Not only in the political sphere, but also in the scientific and educational ones. We are seeing a return to obscurantism. The proliferation of disinformation, and the delegitimization of truth and expert authority appear as new factors that seemed to have been forgotten [71,72].

In conclusion, we cannot and must not limit ourselves to reproducing inherited models or competing solely on metrics. The university must reclaim its educational mission, not just its training role, and exercise its social responsibility as a critical voice and moral beacon. Of course, we must maintain the most demanding technical rigor, but at the same time, the education we provide must be broader, integrating technical knowledge with ethical thinking and social responsibility. Contrary to what many argue, *the university matters today more than ever, although it is urgent to update its long-standing missions.*

III. LESSONS I HAVE LEARNED

As my best professors taught me, a class—and perhaps an academic life as well—should end with a summary of its content and an introduction to the next topic. The preceding pages have been, to a large extent, a reflection on the university at a critical moment in history and on the role that knowledge, and its generation and transmission, can play in that context. This final chapter aims to summarize, necessarily imperfectly, some of the lessons I have learned throughout my academic life.

After almost half a century at the university, one understands that many of the truly important things do not appear in syllabi or textbooks, but are learned slowly, through mistakes, conversations, fortunate encounters, and also failures.

III.1. Transdisciplinary research and training

"The core idea of transdisciplinarity is different: it is the integration and even transcendence of disciplinary worldviews."

Julie Thompson Klein

As we know, scientific progress has been accompanied by increasing specialization. This phenomenon is understandable and, in many cases, necessary. Reductionist logic has been extraordinarily effective in breaking down complex systems into manageable parts and has enabled spectacular advances. Moreover, the complexity of current problems demands a deep mastery of specific tools. However, *excessive specialization carries the risk of narrowing the intellectual horizon to the point of losing the global perspective*. When a researcher limits themselves to optimizing a procedure within a conceptual framework they never question, curiosity is impoverished. Broadening their scope allows them to anticipate consequences, identify analogies, and recognize patterns that are not evident from a narrow perspective.

In my inaugural address to the Royal Academy of Engineering, I reflected on the transition from classical reductionism to more holistic and transdisciplinary approaches [73]. In it, I emphasized that *reductionism and holism are not antagonistic, but rather complementary perspectives*. Transdisciplinarity, as Nicolescu pointed out and as I elaborated in my speech, does not eliminate disciplines; rather, it clarifies and complements them [74]. The key lies in knowing when to delve deeper and when to integrate.

Some time ago, I had the opportunity to read a book by Michael Gibbons and other collaborators entitled "The New Production of Knowledge." It argues that the truly complex problems facing humanity—climate change, waste disposal, scarcity of vital resources, improving health, and combating lethal and chronic diseases, space exploration, and countless others—can only be solved through the coordinated efforts of large multidisciplinary and multi-institutional groups capable of integrating diverse perspectives. The authors argue that the great transformations in knowledge that have been achieved, and are occurring much more markedly and rapidly today, are not the work of isolated individuals, but of research communities [75]. Major problems do not respect national, institutional, or disciplinary boundaries. On the contrary, they require the collaboration of scientists, engineers from diverse disciplines, economists, lawyers, politicians, philosophers, and countless other specialists from research centres, universities, companies, and various institutions. International and transdisciplinary teams are therefore not a cosmetic option, but a necessary structure for advancing the solution to today's major challenges. *Transdisciplinarity is not an academic fad, but a structural necessity of contemporary knowledge.*

It's true that *working at the frontiers involves accepting discomfort, learning new languages, acknowledging ignorance in unfamiliar fields, and being open to mistakes, but it also opens spaces for innovation and doors to unexpected discoveries.* Intellectual growth rarely happens where we're comfortable, but rather when we change our environment, when we collaborate with people trained in different traditions, when we tackle new disciplines and methodologies. *The comfort zone is comfortable, but sterile.*

Figure 18. *Multidisciplinarity, an essential element for solving complex challenges.*

Personally, I've had the opportunity to see that the most interesting advances often arise from unexpected connections between different fields. The most active fields, as the second law of thermodynamics demonstrates, are found at the interfaces. In my own experience, the move towards Biomechanics and Mechanobiology involved precisely transferring tools from solid mechanics to tissue behaviour, engaging in dialogue with biologists and physicians, and reinterpreting classical models in a new context. Each of these steps involved initial uncertainty, adaptation, and, at times, partial failure. But they also broadened my perspective and my capabilities.

I have also championed the need to know and learn from everything and everyone. History, Economics, Art, Ethics, Philosophy, other cultures, and ways of understanding life are not cultural embellishments, but rather extensions of our abilities. History provides perspective, Philosophy compels us to formulate fundamental questions, and aesthetic sensibility refines our sense of structural elegance and allows us to appreciate the formal beauty of Mathematics. Scientists and engineers who are unaware of the historical context of their developments or designs, or the socio-economic implications of their technical decisions, operate with an incomplete vision.

The university must foster not only technical competence, but also the capacity for cooperation and communication, an interest in other disciplines and methodologies, patience with different paces and ways of reasoning and arguing, and ultimately, a broad and borderless knowledge base.

III.1.1. An example of transdisciplinary research: Modelling homeostasis and epigenetics from a deformable solid mechanics perspective

As I mentioned, my life has unfolded at the boundaries between different disciplines, from mechanical and civil engineering to energy and biology. However, in all cases, my greatest interest has been in the mathematical modelling of dynamic systems, as well as in the mathematical tools necessary for their formulation and solution. *I usually define myself as an amateur mathematician, but with an engineering mindset, always keeping in mind the solution of real-world problems, considering the available data and resources.*

From the integrative perspective of mathematics, very different problems can be viewed through the same lens, or rather, a similar formulation. It is not surprising, therefore, that a large part of my work has focused on identifying similarities between phenomena from very separate fields. This was already the case in the first study we conducted on the adaptation of bone tissue. Leveraging our prior knowledge of the theory of damage to structural materials, we established a complete formulation of anisotropic bone remodelling, with well-founded theoretical results and high predictive power [76].

Since then, we have followed a similar approach to understanding other problems of biomedical interest. In recent years, we have applied the principles of control theory and state variables, as well as their analogy with continuum mechanics, to predict various processes of tissue and cell adaptation and also their disruption, as occurs in cancerous processes. In the remainder of this section, I will attempt to briefly describe some of these cases, abstracting from the mathematics and more specialized concepts.

The remarkable resilience of life to diverse and aggressive environments, including extreme pH levels, very low oxygen concentrations, limited nutrient availability, and extreme temperatures, highlights the impressive capacity of biological systems, developed over billions of years of evolution, to maintain their internal stability [77]. This is achieved through various adaptation strategies that operate across multiple timescales [78], from the immediate immune response [79] to long-term evolutionary adjustments that shape the characteristics of species [80]. Between these two extremes lie other crucial adaptive processes, such as homeostasis [81] and epigenetic adaptation [82]. All these work together to ensure individual and species survival. Understanding these mechanisms is therefore fundamental to biology.

To survive and reproduce, living organisms must be robust, tolerate damage, and incorporate repair mechanisms so that their physiological functioning is not compromised by even substantial variations in external conditions. Homeostasis is defined as the set of physiological processes that actively stabilize an organism's internal environment (e.g., temperature, blood glucose, hormone concentrations, etc.). Since Bernard's original ideas and their subsequent development by Cannon [83], the concept of homeostasis has become the central theoretical framework of physiology.

Homeostatic processes result from a complex interaction between organ networks, orchestrated by the brain and the immune system. Thermoregulation in mammals, for example, is a remarkable homeostatic process whose operating principles and structural components show clear similarities to feedback control systems designed in engineering [84].

The human body, for example, possesses a thermal system capable of maintaining its internal temperature within a small range of variation around 37 degrees Celsius. Peripheral thermoreceptors located in the skin and other tissues detect changes in external temperature resulting from environmental disturbances. This information acts as a feedback signal that is compared with the core body temperature. To accurately measure the latter, mammals have internal thermoreceptors located primarily in the hypothalamus, which directly measure the temperature of the blood circulating in the brain, providing an instantaneous measurement of the core temperature.

The hypothalamus, particularly its anterior preoptic region, acts as the central controller. It receives information from peripheral and central thermoreceptors, compares body temperature to the set point, and determines the type and magnitude of the actuator response. It then sends signals through the nervous system to the various effectors responsible for modifying body temperature.

These effectors include several physiological mechanisms. To increase heat production and conserve it in cold external conditions, involuntary muscle contraction (shivering) is activated, the metabolic rate increases—especially in brown adipose tissue—and peripheral vasoconstriction occurs, reducing external heat loss, as well as piloerection, which creates an insulating layer of air. Conversely, in hot conditions, peripheral vasodilation and sweating are activated, cooling the skin surface through evaporation. These physiological mechanisms are complemented by behavioural changes such as seeking shelter, changes in activity, and changes in clothing.

Bone remodelling is another paradigmatic example of a homeostatic process, in which bone mass and architecture are continuously regulated in response to mechanical stimuli and the accumulation of microdamage [85]. This process involves the coordinated action of different cell types, primarily osteoclasts, responsible for bone resorption, and osteoblasts, responsible for the formation of new bone tissue, as well as osteocytes, which act as sensors of the mechanical environment and transmit this information to the former.

Under normal conditions, bone maintains a dynamic equilibrium between these two processes, so that the total amount of tissue is kept within an appropriate range to ensure mechanical strength and functionality. When bone tissue experiences higher than usual load levels, new bone formation is activated, increasing its density and strength. Conversely, when loads decrease, resorption is favoured, reducing bone mass. This equilibrium can also be interpreted as the result of a homeostatic control system, in which the controlled variable—bone density or porosity—adapts to the mechanical environment the bone is subjected to at any given time [86].

Both cases are examples of systems that function as control systems, with finely tuned negative feedback loops involving sensors, control centres, and effectors, analogous to their artificial counterparts [87]. Furthermore, *they exhibit key characteristics of robust control systems*, such as the use of multiple types of redundant effectors, so that if one mechanism proves insufficient or compromised, others can compensate [88]. Secondly, they typically integrate multiple signals and coordinate multiple responses in complex decision-making processes that go beyond simple binary control. Also, biological responses are usually gradual and modulated in intensity, rather than being activated abruptly, which contributes to the system's stability. Finally, biological systems exhibit a remarkable tolerance to uncertainties and disturbances, maintaining their functioning within acceptable ranges even under adverse conditions.

The homeostatic processes described above assume the existence of a fixed reference value against which controlled variables are compared. However, in many biological systems, this hypothesis is insufficient to explain observed long-term behaviour. Organisms not only maintain their internal variables within certain ranges but are also capable of adapting these ranges when environmental conditions change persistently, as occurs with seasonal temperature changes, in microgravity environments, or after prolonged illnesses. This adaptive capacity is largely associated with epigenetic mechanisms in situations where external conditions persist for extended periods.

Epigenetics refers to the set of molecular mechanisms that regulate gene activity without altering the underlying DNA sequence. These mechanisms include DNA methylation, post-translational histone modifications, chromatin remodelling, and the spatial reorganization of the genome within the nucleus. Collectively, they determine how genetic information is transcribed, shaping cellular identity, lineage commitment, and the ability of cells to respond to environmental stimuli [89].

The stability and reversibility of epigenetic marks allow cells to integrate signals from their microenvironment and store information about past exposures, endowing tissues with a form of molecular memory. This memory, however, is neither perfect nor permanent, as epigenetic changes can be reversed over time, but it provides an essential adaptive capacity for survival in changing environments [90].

From a modelling perspective, *these processes are often formulated within control theory*. This allows for the application of widely developed mathematical and numerical tools to the biological domain. *These concepts find a natural interpretation in various fields of state-variable thermodynamics* [91], and, in particular, in viscoplasticity [92], or the mechanics of continuum damage [93]. For example, the homeostatic region is easily identifiable with its elastic equivalent in the external stimulus space, as is the recovery of the homeostatic state with changes in plastic deformation or damage, and the evolution of these changes with the flow law of internal variables. This allows, for example, the direct use of algorithms employed in nonlinear mechanics to solve complex biological problems, as well as thermodynamic results for a better interpretation of underlying metabolic processes.

In this context, epigenetics can be interpreted as a mechanism that modifies the parameters of the control system, allowing the system to readapt to new conditions. For example, in bone remodelling, given a prolonged absence of mechanical load, as occurs during long periods of immobilization, the system reduces the level of density considered optimal, leading to a decrease in bone mass. This process cannot be explained solely by classical homeostasis but requires the incorporation of an additional level of regulation.

Epigenetics can thus be interpreted as a meta-control that acts upon the control system itself, adjusting the regulator's parameters and, in particular, the reference region within which the system considers functioning adequately. This meta-control operates on longer timescales than those associated with homeostasis. Consequently, the system responds not only to the instantaneous state of external stimuli but also to its history.

From a methodological standpoint, this phenomenological approach based on input-output relationships avoids the need to describe all the underlying molecular mechanisms in detail, which would be unmanageable in many cases. Instead, the essential characteristics of the system's behaviour are captured through state variables and evolutionary laws that can be identified from experimental observations. This strategy facilitates the construction of manageable and potentially predictive models. Referring to its mechanical equivalent, epigenetics modifies the elastic domain, being equivalent to plastic hardening variables or changes in the damage criterion. One important point to highlight is that mechanical processes in inert materials are not usually repairable (except in some specific cases, such as self-healing materials), while homeostatic or epigenetic processes are, requiring modifications to classical mechanical theories of inert materials to include this possibility [94].

Another illustrative example of this type of behaviour is found in the acquisition of drug resistance in tumour cells, as occurs in glioblastoma cells treated with temozolomide. Cells exposed to the drug for extended periods develop epigenetic changes that modify their response, progressively reducing the effectiveness of the treatment. This process cannot be explained solely by homeostatic mechanisms but requires the consideration of epigenetic changes.

Glioblastoma (GBM) is one of the most difficult diseases to treat in oncology [95]. Despite its low prevalence (incidence of 3 cases per 100,000 person-years [96]), it is the most common primary malignant tumour of the central nervous system, accounting for 48.6% of all cases [97]. It is also the most lethal brain tumour, with a five-year survival rate of 6.8% [98] and a median survival of approximately fourteen months after diagnosis in patients who have received current standard treatment [99, 100].

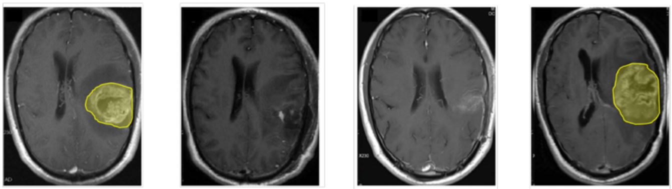

Figure 19. *Recurrence of glioblastoma multiforme.*

The current treatment is the Stupp protocol [101], which consists of maximal safe surgical resection followed by radiotherapy with concurrent and adjuvant chemotherapy using temozolomide (TMZ), the only drug approved for this protocol. The treatment regimen, according to this protocol, consists of six 28-day cycles, with TMZ administered for the first five days of each cycle at a daily dose of 150–200 mg/m² (milligrams per square meter of body surface area). However, this treatment only increases median overall survival from 12.1 to 14.3 months [102]. Since its approval in 2005, and despite considerable efforts, there have been no significant advances in the treatment or survival rate of this tumour [102].

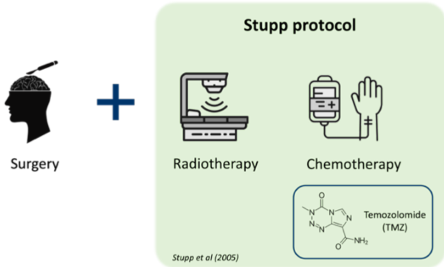

Figure 20. *Stupp protocol for glioblastoma treatment.*

TMZ is an oral alkylating agent that acts on glioblastoma multiforme (GBM) cells by inducing epigenetic changes [103] that lead to phenotypic plasticity [104]. Both elements were included in 2022 among the characteristic markers of cancer [105]. Specifically, the mechanism of action of TMZ involves inducing methylation at various DNA bases. It affects proliferating cells, inducing cell cycle arrest and thus preventing their duplication (i.e., causing a cytostatic effect), which ultimately leads to apoptosis [106, 107]. However, more than 50% of patients with glioblastoma multiforme (GBM) do not respond to TMZ treatment [99], due to intrinsic and acquired resistance of GBM cells to chemotherapy. In fact, these cells can reverse the epigenetic changes induced by TMZ and recovering their normal proliferative behaviour [108]. Induced resistance is primarily associated with overexpression of the O6-methylguanine-DNA methyltransferase (MGMT) protein, which can repair TMZ-induced DNA damage by removing methyl groups attached to DNA [109]. Other mechanisms of acquired resistance exist, such as the emergence of cancer stem cell populations [110].

To overcome the stagnation in the development of new treatments for this tumour, a better understanding of the mechanisms that trigger chemoresistance is essential. Three-dimensional culture models are the most suitable in vitro tools for reproducing tumour behaviour and drug response, as they allow for the faithful imitation of in vivo physiological conditions, both structural and functional. Among these techniques, spheroids are the most widely used [1101], due to their ease of cultivation and their ability to reproduce cell-cell interactions and gradients present in solid tumours [112]. In our work, we focused on the results obtained by our group in a previous study, where spheroids from the commercial glioblastoma cell line U87 were treated with TMZ following the clinical protocol. Two different responses were observed. While one group of treated spheroids showed growth stagnation that persisted throughout the experiment, another group developed resistance and was able to resume growth, despite subsequent TMZ administration.

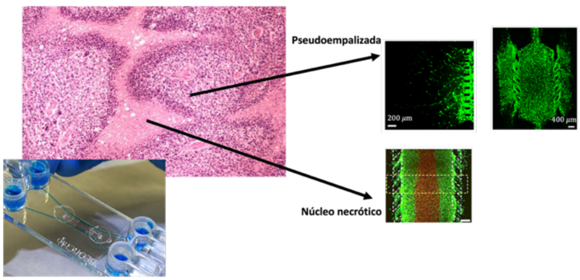

Figure 21. *In vitro model of pseudopalisade formation and necrotic core of glioblastoma.*

The main objective of our work was to develop a mathematical model that incorporates the acquisition of resistance in glioblastoma, to quantitatively reproduce the aforementioned experimental results. The model considers temozolomide-induced cell adaptation and its cytostatic effect, as well as the eventual repair of these changes that leads to the development of resistance. In previous work by our group, a general framework for modelling cell adaptation was proposed, including the cell phenotype defined by a set of internal variables that describe the cell state [113]. Following concepts from control theory and a well-known formulation in continuum mechanics, an evolution equation was derived for each internal variable, and its effect on cell behaviour resulting from changes in the values of these internal variables was modelled, allowing coupling with the microenvironment and cell evolution.

This model was specifically tailored to the problem of adaptation of spheroid-shaped glioblastoma cells to temozolomide, and its parameters were calibrated to match the experimental data. Once validated, we analysed the model in relation to biological questions, such as the cause of the differences between the two spheroid populations (those that develop resistance and those that do not).

Interestingly, in the numerical experiments, we observed that the second treatment cycle had no effect on cell behaviour, suggesting that the same cells treated with a single cycle of temozolomide between days 0 and 5 should exhibit a similar evolution to those treated with two cycles. This was experimentally confirmed by subjecting glioblastoma spheroids to a single cycle of temozolomide and allowing them to rest until day 56.

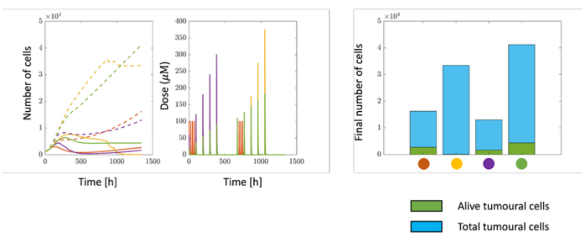

Figure 22. *Evolution of the size of spheroids and tumour cells after several treatment cycles.*

These preliminary results exemplify the usefulness of mathematical models, such as the one presented here, for proposing new hypotheses and identifying key mechanisms or variables in a complex process like the acquisition of chemoresistance. Furthermore, they show how models help reduce the number of experiments required in the laboratory, decreasing associated costs and highlighting experiments that could generate greater knowledge. Of course, further validation is required to verify whether the model can generalize and accurately predict the evolution of spheroids under different treatment regimens. Finally, a fully validated model could function as a digital twin of the spheroids and be used to determine the optimal treatment for achieving tumour remission in real patients.

The initial tests performed are consistent with previous findings in clinical trials, which suggest that prolonged or high-dose-density regimens do not improve survival [114] (in our case, the spheroid grew similarly to the clinical treatment). The main finding suggests that regimens with variable and increasing doses throughout the cycles could be beneficial, as the tumour does not have the opportunity to adapt to high doses in the initial cycles. Although conclusions must always be validated with experimental data, the results obtained allow us to narrow down the possible solutions, reduce the necessary but costly clinical trials, and identify possible causes for the observed results, demonstrating once again the value of transdisciplinary research.

III.2. The role of chance. My life in a nutshell

"Success = talent + luck. Great success = a little more talent + a lot of luck."
Daniel Kahneman

At this point, I will try to show how a life is not predetermined by the specific conditions of one's birthplace and family upbringing, although these undoubtedly have a decisive influence. I will demonstrate, through my own example, how particular circumstances, seemingly inconsequential decisions, or people and examples at a particular moment are as important as, or even more important than, effort or talent.

I don't intend to give any examples, nor to focus on what I have done, but rather on why I did it—reasons that are, far more often than one might imagine, the result of chance, or the fortunate coincidence of moment, place, and circumstances, and not of reflection or deliberate decision-making. This does not invalidate perseverance and preparation. On the contrary, it makes them even more valuable, since one must be prepared so that, when those moments arrive, you can choose the best option, and, of course, so that those who make the decisions think of you as a potential beneficiary. *As I've told my son so many times, you must open as many doors as possible so that, in some of them, you'll be invited in.*

However, this recognition of the role of chance, therefore beyond our control, does relativize personal merit. There are many with the same or even more merit than us who aren't there when the door opens, or the person who opens it doesn't consider them for various reasons, or simply, they didn't have those by their side who prevented them from turning back in moments of doubt, or who offered them a hand, once inside, to delve deeper and continue opening others. Immediate corollaries include the obligation to return the favours to those who are now in the same situation you were in, and the recognition that the reasons most don't reach the end of the road aren't laziness, lack of motivation, or lack of willpower, but rather that they didn't have the good fortune that others of us had.

In my case, I've had support at every moment of my life and in every circumstance, for which I must be grateful. I was born in Córdoba in 1956, into a typical family of that time: my father worked in the civil service and my mother was a homemaker, although, as is so often the case, she possessed greater intelligence and perseverance than the rest of the family. This was demonstrated when she had to start working later in life to raise her four children after my father's premature death at the age of 34 (I, the eldest, was 7). Parents back then, and my mother was no exception, were convinced that education was the path to advancement, so, with everyone's help, including the government, she turned a deaf ear to our financial situation and gave us the opportunity to study, in my case, even away from my hometown.

I was fortunate, both in primary school and secondary school, to have excellent teachers who instilled in me a love of learning and a fascination with mathematics.

My dream was to study Telecommunications Engineering. Unfortunately, or perhaps fortunately, as we'll see later, my family's finances didn't allow me to move to Madrid, the only place where it was offered at the time. So, the solution was to study Industrial Engineering, specializing in electrical engineering, in Seville.

Figure 24. *Lucio Anneo Séneca High School (Córdoba).*

After three years pursuing this dream, when it came time to choose a major, a roommate in my student apartment suggested I also enroll in Mechanical Engineering, using the excuse that I wanted to keep him company, since he wasn't as sure about his future as I was. When, after I repeatedly refused, he insisted, arguing that I could drop out whenever I wanted and that, moreover, it wouldn't cost me anything since I had a scholarship and free tuition, I finally agreed, following my worst flaw: not knowing how to say no. I enrolled in both specializations, electrical and mechanical, with the clear intention of attending a few classes in the latter and then dropping out soon after. Who could have foreseen then that this seemingly insignificant decision would change my life?

Figure 25. *School of Industrial Engineers in Seville in 1975.*

I reluctantly attended my first Mechanics (Strength of Materials II) class, taught by a young professor recently arrived from Madrid. His name was Enrique Alarcón, and he told us he would be explaining the Theory of Elasticity and that, for that, it would be helpful to know something about tensors. He then launched into explaining what these tensors were (which we had never seen before) and how to work with them. I have to confess that I understood almost nothing, but I was fascinated. For the first time, a professor was showing me that complex mathematics could have practical applications. Moreover, his way of explaining, his conviction, his charisma, and the enthusiasm of the recent graduates who were with him did the rest. I continued with that subject until the end of the semester, and for the first time in my entire degree, I tried to learn it and not just pass it. I bought books outside the syllabus, I worked hard to understand, and soon I approached his department to ask to work on any topic and with whomever I could. Although I finished both specializations, there was no going back.

Figure 26. *Enrique Alarcón and his wife, Pilar in Sevilla in 1976.*

The following year, Enrique left many of us feeling orphaned, moving with some of his students to the Chair of Structures at the School of Industrial Engineering at the Polytechnic University of Madrid. I only learned this later, as I was quite busy completing my military service and the dozens of exams I had to face to finish my studies. Just after finishing them, I received a call from one of Enrique's students, Rafael Picón, who had remained in Seville in charge of the Chair and who, at the time, had supervised my work there. Rafael offered me a position as a teaching assistant for practical classes in Strength of Materials, which I accepted without much hesitation. In October 1978, I began my academic career.

Figue 27. *Rafael Picón in 1980.*

After a year of struggling with the subject, a new opportunity arose when Rafael invited me to accompany him to some courses in Madrid, taught by Enrique and his collaborators, on Matrix Calculus and Dynamic Analysis of Structures. We set off in his beat-up car, on a journey of almost eight hours. I reconnected with Antonio Martín and Federico París, who are here today, and José Domínguez, who sadly passed away a little over a year ago. After the courses ended, as we were leaving the parking lot of the

Madrid School of Engineering, Enrique told me that Rafael, ever generous, preferring to lose his only collaborator to open doors for him to a better future, had conveyed my interest in going with him to Madrid. Stammering, I confirmed it, to which he replied, "We'll talk about it."

In September 1979, I began my most fruitful period of training at the Madrid School of Engineering. Long days spent preparing classes, problems, and assessments for subjects I hadn't even been taught yet, working on projects for companies, and learning the art of research with the beginning of my doctoral thesis. But we also had time to attend seminars and conferences, to enjoy the life of young people eager to take on the world. In June 1980, I married my longtime girlfriend, Conchi, and we moved, along with my colleague and friend Francisco García Benítez, to the Civil Engineering department at the University of Southampton, to join the world's leading group in Boundary Elements, led by Professor Carlos Brebbia, to make progress on my thesis topic. Another two frenetic months followed, during which my new wife and I saw each other in the evenings, and we dedicated a few weekends to visiting places of interest. However, I not only returned with my thesis more than partially written, in the form of punch cards in a backpack, but I also experienced for the first time the exhilaration of being in another international group, speaking another language, and making new contacts.

We returned to Madrid, and after a few months, Enrique told me I had to submit my doctoral thesis "immediately," because he wanted me to apply for an assistant professorship (now a tenured position). I replied that it wasn't possible, not even working around the clock. "Then we'll change the thesis topic," he answered. Imagine this situation today, and we'd agree that my positive response could only have come from the absolute trust I had in my mentor. "If you think I can do it, I'll start tomorrow," I replied.

Indeed, in May 1981, I submitted the thesis, after two sleepless nights, and with the invaluable help of all my colleagues and my wife, who typed the more than 400 pages it comprised.

Figure 28. *Members of Enrique Alarcón's group in Madrid in 1981.*

I signed the position on time, and with barely a moment to breathe, Enrique and one of the members of my thesis committee, Professor Alberto Dou, a leading figure in Spanish mathematics, offered me a postdoc position at a mathematics centre. Again, without much hesitation, I accepted, and after securing a Fulbright scholarship, I was accepted at the Courant Institute of New York University, then a mecca of world mathematics with several Fields Medal winners among its ranks. In September 1981, Conchi and I moved to New York. Another wonderful experience, not only because of the city and the friends we made, but also because, for the first time, I encountered cutting-edge research. A very tough learning experience, being so far removed from my engineering background, but fundamental for my future. During that same period, and on a whirlwind trip to Spain, I obtained a position as an assistant professor in Madrid, where we returned the following academic year.

Figure 29. *Courant Institute of Mathematical Sciences. New York University,*

Little changed in my life during the following two years, apart from some additional responsibilities and my appointment as Professor of Structural Theory at the School of Industrial Engineering in Zaragoza in 1983. Before moving on to this stage, I must emphasize that, up to that point, I had few decisions to make, only to follow the advice and guidance of my mentor, with the absolute conviction that they represented the best option for my future. At that time, Enrique offered me the opportunity to stay in Madrid, promising that I would soon obtain a professorship. I was faced with a dilemma: remaining in Madrid was the safer option. Under his guidance, in the place and with subjects I already knew, with contracts with companies, laboratories, and resources, in our apartment, with our friends, and a future full of possibilities at the most sought-after school in Spain. The alternative was to begin a new chapter on my own, with few points of reference, a new school, without a building, laboratories, computers, or collaborators, in an unfamiliar city, but free to choose and make mistakes. I opted for the latter, and I wasn't wrong, not only for my personal growth, but even more importantly, because it helped me maintain, until the very end and without any friction, something crucial to me: the father-son relationship with Enrique.

In June 1984, Conchi, pregnant, and I moved to Zaragoza with the clear idea of returning to Madrid or Seville after a few years, with the necessary experience. The beginnings were tough, without any resources, trying to make my way, with endless hours working with my first student, Luis Gracia, and with the birth of our son, Alberto. However, in the very young school in Zaragoza, I found an atmosphere full of young colleagues, many of them, like me, from other cities and with experience abroad. Moreover, it seemed as if we had sworn an oath to make the school one of the best in Spain. All of them, most now retired, and some deceased, have been part of my family, not only because of intellectual and personal closeness, but also because I spent more time with them than with my wife and son. José Manuel Correas, Felipe Pétriz, Francisco Serón, Rafael Navarro, Rafael Bilbao, Jesús Arauzo, Javier Castany, Antonio Valero, César Dopazo, Manuel Silva, and many more from the first graduating class, along with the warmth and support of our many friends outside the School, convinced us to make our lives here.

Figure 30. *interfacultades and Torres Quevedo buldings of the ETSII at Zaragoza,*

I cannot dwell on everything that has happened in these more than forty years. I will only highlight a few points that, aside from being milestones in my life, illustrate what I believe should be part of the university spirit. In 1985, following the implementation of the University Reform Law in

Spain, departments were created for the first time as groupings of areas of knowledge. Their formation was a turbulent process, in which, on too many occasions, personal likes and dislikes took precedence over scientific requirements. From the outset, I was convinced that my department should have an internationally recognized name and standing. Thus, the Department of Mechanical Engineering at the University of Zaragoza was established, and I was appointed its first director. This decision later allowed our university to be selected to participate in the ECTS pilot phase of the newly created Erasmus program, in one of the five-degree programs that comprised this pilot program—precisely mechanical engineering. This allowed me, as scientific coordinator, to participate in the initial decisions, and for our university to be, for many years, the Spanish institution that sent and received the most engineering students in Europe.

In 1990, after my time as deputy director and director of the Mechanical Engineering department, my commitment was to accept the directorship of the Higher Polytechnic Centre, a position then decided almost by co-option. However, after six years continuing the line of research I had inherited from Madrid, I was eager to find my own, one with a more promising future. So, I told my good friend Manuel Silva, who also recently passed away, that I couldn't succeed him as director, as had been agreed, because I had obtained a sabbatical year to go to the United States. He replied that he was happy for me, but that he would run again for the directorship so that, after his second term ended, I could fulfil my obligation, which I did.

The entire family's stay at Stanford University was extraordinary. New friends, new places, and a stimulating environment. For me, it was a return to world-class research, a chance to confront my insecurities and limitations once again, but also to relish the learning experience, not only scientific but also personal. I was fortunate enough to work again with Juan Carlos Simó, originally from Spain but now permanently based in the US and considered one of the world's leading figures in Computational Mechanics. From Juan Carlos, who sadly passed away at the age of 42 in the prime of his human and scientific abilities, I learned the depth of mathematical analysis and its relationship to the underlying physics. My subsequent exploration of nonlinear solid mechanics owes much to his teachings.

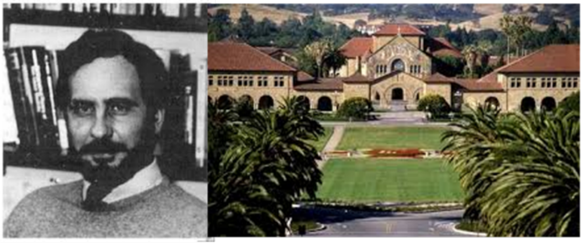

Figure 31. *Juan Carlos Simó and Stanford University in 1990.*

This time at Stanford allowed me to gradually move away from my work on boundary elements and into nonlinear continuum mechanics, opening the door to new applications. The most important, without a doubt, was biomechanics, and later mechanobiology and tissue and cell engineering, which I again approached not as a deliberate decision, but rather by chance. In 1998, shortly after leaving my position as director of the School, I received a visit from a colleague, now a friend, from the Faculty of Medicine, specifically from the Department of Traumatology, Dr. Daniel Palanca. After introducing himself, he told me that he had heard about me as an expert in finite elements and that he would be interested in knowing if I could conduct a comparative study of different pelvic fracture fixations. After a few questions and driven by my own ignorance and desire to help, I replied that I could. We started with a final year project on the topic, where I immediately realized that the problem wasn't with fractures or steel fixations, which I knew how to model, but with the behaviour of bone tissue. After some further study, I suggested to a doctoral student, José Manuel García, that he change his recently begun doctoral thesis on plasticity to the modelling of bone remodelling, based on the hypothesis that predicting the evolution of bone porosity could be done using the principles of Continuous Damage Mechanics. That was the beginning of a complete reconfiguration of my research group in the following years, which became one of the most powerful in our country in Biomedical Technologies. Once again, luck paid off.

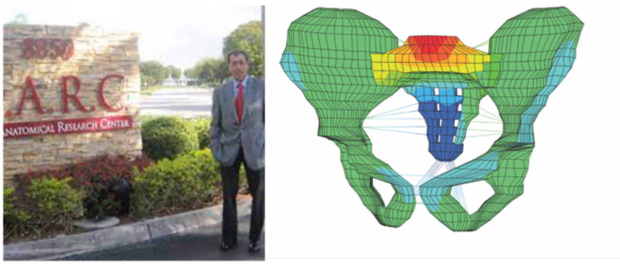

Figure 32. *Daniel Palanca and our first results on pelvic fixations in 1998,*

The period from 1991 to 1997 at the School of Industrial Engineering in Zaragoza was frenetic. The number of students tripled, straining the buildings and resources to their limits; the degree programs expanded from one to four; there were changes to the curriculum and the name, becoming the Higher Polytechnic Centre (CPS). There was construction in the hallways, three class shifts from 8 a.m. to 10 p.m., and a massive influx of young professors. In short, a turbulent but exciting period that tested our resilience and cohesion. Fortunately, the construction and opening of a new building, along with the natural course of events, meant that by 1999, the CPS was reasonably well established.

Around that time, during numerous conversations over meals with my friends and colleagues at the School, the idea surfaced that not moving forward is falling behind, that the infrastructure and teaching capacity were already strained, and therefore, if we wanted to maintain unity and enthusiasm, we should propose ambitious initiatives in other areas. After advocating for the need to coordinate and structure research at the School (again, my obsession with uniting to achieve greater goals), I was tasked with creating a research institute. After looking into it, I saw that the idea wasn't new at our university, but that the widespread belief that institutes were one-person initiatives, akin to cronyism, had hindered the progress of other proposals. Armed with the support of the entire School, I felt empowered to defend the obvious rejection of that notion, at least in our case. After presenting the idea to unions, business organizations, university groups, and other members of the Social Council, and with the invaluable support of the then-rector, Felipe Pétriz, the creation of the first university institute at the University of Zaragoza, the Aragon Institute for Engineering Research (I3A), was finally approved. I was its first director, and fortunately, many others followed, definitively changing the way research was conducted across the Aragonese university system. How a simple dinner table conversation can change our reality.

In 2006, another chance encounter changed my life. That spring, I was invited to attend a conference on biomedical research, organized by the Aragonese Institute of Health Sciences at the Rueda Monastery. The then-director of the Carlos III Health Institute, Francisco Gracia, whom I didn't know, was participating. After being introduced, I recognized him as the son of the headmaster of my public school in Córdoba. In his speech, he mentioned the upcoming creation of seven networked biomedical research centres (CIBERs) for different families of diseases, with the aim of boosting and coordinating biomedical research and its translation into the Spanish healthcare system. These centres would be comprised of groups of excellence selected by international committees. Afterward, I introduced myself, reminded him of our childhood, and asked if the CIBER census was complete. He replied that it was and asked why I was asking. I explained that I didn't understand why there wasn't a CIBER that considered research in technologies related to the health sector in its broadest sense. After a moment of reflection, he invited me to Madrid to present the idea. At the time, I was a relatively unknown researcher in the field, so I decided to go as prepared as possible. After traveling throughout Spain, I secured the endorsement of the main Spanish research groups, which I used to present myself to the top management of the ISCIII (Carlos III Health Institute), accompanied by the director of the IACS (Institute of Applied Sciences and Biotechnology), Esteban de Manuel, and the then Minister of Economy of Aragon, Alberto Larraz. After the presentation and the relevant questions, we left with positive feelings, but lacking hope. A few weeks later, the Royal Decree creating the CIBERs (Regional Centers for Biotechnology Research) was published, including an unforeseen one on Bioengineering, Biomaterials, and Nanomedicine, which completely changed the landscape of health technology research in Spain and the international standing of our group, demonstrating once again that chance can shape lives.

Figure 33. *Cover of the first information brochure of the I3A and CIBER-BBN.*

After my term as the first director of CIBER-BBN, I faced the same old question: how to move forward? Coincidentally, the future Health Engineering degree program at the University of Seville was being developed at that time. My friends, Jaime and José Domínguez (Pepón), invited me to get involved in its curriculum and suggested I move to Seville to promote the program. I already had strong connections with the director of the Institute of Biomedicine of Seville, José López Barneo, and two PhDs from my research group, José Antonio Sanz and Esther Reina, at the engineering school in the same city. So, without having made a decision, I had several conversations with the university rector. After realizing that his intentions didn't align with mine, I decided to travel to Seville to inform my friends of my decision not to accept and to thank them for their efforts. Pepón arranged to meet me at a well-known bar in Seville, and after I explained my decision, he asked if, being "free," I could consider another offer. He then told me about his idea to create a small company within Abengoa, a well-known multinational conglomerate in the field of renewable energy and sustainability, where he was then the technical secretary general. This company would conduct higher-risk, longer-term research than was already being done in the group's various companies. "Would you be interested in the position of scientific director?" he asked. Pepón was a charismatic and persuasive person with unparalleled charm, but I wasn't sure that this type of research could be done within the Spanish company, which is why I declined his offer. He, who never did anything without a reason, then asked me to review the CVs they were receiving from candidates for positions within the company. "Of course, no problem," I replied.

Shortly afterward, he sent me around 90 applications out of a total of almost 900 received. I got to work on the project, and to my surprise, I discovered that doctors from Max Planck, Yale, and many other world-class universities wholeheartedly endorsed the idea Pepón had shared with me. I then requested another meeting so he could explain his idea in more detail. After discussing the novelty and potential of this proposal and explaining that the administration and management would be handled by others, and that I would have the budget and freedom to hire whomever I chose, he invited me to Seville, where "our president, Felipe Benjumea, will surely convince you." Once in Seville, and after the introductions, Felipe uttered a single sentence: "Everything Pepón told you is true." Convinced, I accepted the offer, aiming to expand my experience in private research.

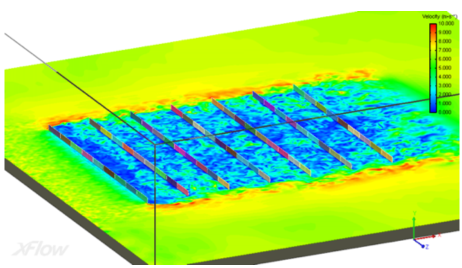

Figure 34. *Wind loads on a solar field. Application at Abengoa Research.*

I must admit that what was promised to me was delivered. In just a few years, Abengoa Research went from non-existence to becoming the Corporate Research Centre for the entire Abengoa group, one of the 35 largest Spanish companies (with more than 30,000 employees in 80 countries and €8.5 billion in annual revenue). In 2015, AR had more than 400 employees (300 researchers and technicians, 82 PhDs, and 15 doctoral students), 6 divisions, with centres in Spain and the United States, a budget exceeding €50 million, state-of-the-art laboratories, and the responsibility of making Abengoa a world leader in renewable energy and sustainability. At that time, we generated around 60 patents, dozens of publications, and worked on more than 50 projects annually, approximately half of which were funded by the EU, making us one of the most important private research centres in Spain.

Financial problems forced Abengoa to interrupt its research work, so I resigned and returned to Zaragoza, where I resumed my academic career in June 2016. However, during the five years I spent with that group, I was fortunate enough to meet people of immense professional and personal worth, who have become lifelong friends. Some are with me today; others couldn't be here. I also shed prejudices, learned new ways of approaching research and management, and how to lead large groups in different parts of the world. Furthermore, and no less importantly, it allowed me to experience life and the unique character of Seville, become a member of Betis and a fair booth, and reconnect with or forge new friendships.

I hope I have made clear the importance of certain moments, circumstances, and people in each person's personal and professional journey. Chance plays a role in our lives, making personal merit just one more, albeit essential, element that defines our existence.

III.3. Lessons I've learned. A final message to young people.

"If I have seen further, it is by standing on the shoulders of Giants"
Isaac Newton

The university today finds itself at a historic crossroads that, while sharing features with other crises it has faced throughout its history, presents new characteristics that demand profound reflection on its role in contemporary society. For the first time in centuries, the university is losing its monopoly—or at least its clearly dominant position—in the three functions that have traditionally defined its institutional identity. The first of these is research. For much of the 20th century, most advanced scientific research was conducted in universities and public research centres. Today, however, a growing proportion of the most advanced knowledge is generated in large technology companies, industrial laboratories, or private innovation centres. Sectors such as artificial intelligence, biotechnology, and digital technologies clearly demonstrate this paradigm shift, as a high percentage of the most influential scientific contributions now come from organizations operating outside academia.

Figure 23. *Bay View* Google's ***C****ampus at Mountain View, California.*

The second function that the university has ceased to monopolize is the transmission of knowledge. For centuries, access to specialized knowledge was almost exclusively mediated by university institutions. Today, that landscape has changed radically. The internet, digital educational platforms, open online courses, and various forms of professional or business training have multiplied the channels for accessing knowledge. Millions of people are now acquiring advanced skills outside of traditional educational systems, through resources that were unthinkable just two decades ago, to the point that many are beginning to question the real usefulness of university studies.

Another significant change is occurring in a third area: the construction of informed opinion in society. For a long time, university professionals—scientists, lawyers, philosophers, or economists—not to mention teachers, played a central role in public debate. Their reflections helped guide social discussions on complex issues. Today, that space has been profoundly transformed. Social media, new digital media, and the so-called attention economy have generated a communication ecosystem in which influence does not necessarily depend on intellectual rigor or expert knowledge. Influencers, YouTubers, TikTokers, and other media actors can shape public perception on scientific or technological issues with an effectiveness that surpasses the capacity of the academic community to intervene.

This phenomenon is part of the tremendous transformation that the knowledge ecosystem is undergoing in contemporary societies, and it compels universities to rethink their role with intellectual honesty. If they no longer hold a monopoly on research, education, or the construction of informed opinion, what then is their function in the 21st century?

The answer cannot simply consist of trying to compete with these new actors on their own turf, as some purely utilitarian universities and centres have decided to do. Universities will not be able to surpass large technology companies in financial capacity for applied research, nor compete with the internet in the mass dissemination of information, nor fully adapt to the accelerated logic of digital communication. Attempting to do so would likely lead to frustration and the loss of its deepest identity.

The future of the university lies, rather, in reinforcing what has historically constituted its uniqueness. Faced with the speed of digital information, the university must reaffirm the value of rigorous analysis and critical thinking. Faced with the inevitable simplification of messages in the media landscape, it must offer depth, context, and intellectual coherence. Faced with the fragmentation of contemporary knowledge, it must remain one of the few spaces where different disciplines engage in structured dialogue. Faced with moral relativism, contempt for truth, and biased or simply hateful rhetoric, it must reinforce its intellectual and social honesty and maintain its role as a moral beacon.

In any case, its most valuable contribution will continue to be something else: the personal relationship between generations of university students. Close, honest, and demanding mentorship is one of the most fruitful traditions of university life, and the most difficult to replace with any technology. Throughout history, much of scientific progress has arisen precisely from that direct relationship between teacher and student who share questions, methods, and values. In a world where information is abundant but intellectual guidance is scarce; the role of the mentor takes on renewed importance.

Ultimately, the future of the university will depend on its ability to reaffirm the values that have underpinned its legitimacy for centuries: intellectual coherence, formal rigor, ethical integrity, and a commitment to training new generations capable of independent thought. In a world characterized by the volatility of information and the relativization of many cultural and moral reference points, these values may seem modest, but they probably constitute the most solid foundation upon which a relevant university can be built in the 21st century.

Despite all the uncertainties I have described throughout these pages, it would be a mistake to conclude with a pessimistic view of the future. A detailed study of human history demonstrates that, from a long-term perspective, the improvement of the conditions in which we live is constant [115]. However, in the short term, terrible distortions can occur, and it will be our responsibility.

Figure 35. *The university, an essential component in the society of the future.*

There are profound reasons for optimism. Never before has humanity possessed a scientific, technological, and creative capacity comparable to the one we have today. The very tools that generate unease—artificial intelligence, biotechnology, global knowledge networks—also offer extraordinary opportunities to better understand the world and to solve problems that for centuries seemed insurmountable. Contemporary science is developing at a speed and with a capacity for international cooperation that is unprecedented in history. Teams of researchers from different continents are currently working together on problems such as fusion, cancer, pandemics and vaccines, increasing food and resources, reducing waste, and mitigating and even reversing the effects of climate change, the solution to which will decisively improve the lives of millions of people.

As an example of this optimism, I would like to mention the intriguing concept of respirocytes [116]. These are artificial red blood cells with performance far superior to biological ones. Although we are not yet able to solve all the engineering problems that will allow us to build them, when we succeed, we will only need to breathe once every two hours.

In this context, the university will remain one of the few spaces where knowledge can be cultivated with the depth, freedom, and critical thinking that human progress requires. If it is able to preserve its intellectual rigor, its independence, and its commitment to service, it will continue to be an indispensable institution for forming free citizens, responsible scientists, and professionals committed to the collective well-being. As long as there is a community of people willing to ask questions, to doubt, and to learn from one another, the university will remain vibrant and maintain an essential role.

With the wisdom of age, if I could speak today with the student I was so many years ago, I would try to summarize everything I've learned in a few simple ideas:

- *Education is not about transmitting information, but about teaching people to think, to question, to make mistakes, and to correct them.*
- *Learning and generating knowledge freely is both a privilege and a responsibility.* Knowledge must be shared, expanded, and directed toward the common good.
- *Curiosity is the true engine of knowledge.* We don't research because we have to publish, but because we want to better understand the world.
- *Research is a form of service that allows us to improve people's physical, intellectual, and social lives.*
- *Incremental research is necessary to advance knowledge, but disruptive research changes our lives;* therefore, without neglecting the former, we must nurture the latter.
- *Major problems do not respect disciplinary boundaries.* The most fruitful ideas often arise when different fields connect.
- *Learning beyond what is useful broadens our perspective.* Science also needs history, philosophy, art, and culture to fully understand its own meaning.
- *The generation of scientific knowledge is a necessary condition for technological progress, but not a sufficient one.* For knowledge to transform into innovation, a complex ecosystem is needed where researchers, businesses, research centres, public administrations, and investors interact. The university must learn to contribute to this ecosystem without relinquishing its intellectual independence.
- *The university is a conversation between generations. No one builds an academic career in isolation. Every step we take rests on the work of those who came before us and on the generosity of those who work with us.*

- *The university must focus on its essence: to educate curious, critical, and morally responsible individuals, capable of working at the frontiers of knowledge and understanding that technology is not an end in itself, but a tool at the service of society.*

I would like to conclude, with the privilege of age, by offering ten pieces of advice to younger people:

- *Be grateful* to those who came before you and to those who help you in your work.
- Be generous. Science is open and must be shared down to its last elements.
- *Be curious, always ask "why?", don't settle for superficial answers.* Knowledge broadens perspectives, and science needs the humanities.
- *Be responsible.* Remember that the success of a life is not measured by accumulated accolades, but by the good one has contributed to generating.
- *Be humble.* Although talent and effort help progress, chance is decisive, so put your merit into perspective.
- *Be loyal* to the people who accompany you and the institutions that support you.
- *Be supportive* of those who have not had the same fortune as you.
- *Be persistent,* because depth requires time. Long-distance races are won by those who do not give up.
- *Be demanding of yourself,* because self-discipline is a sign of respect for yourself and others.
- *Be brave, try things, make mistakes. The comfort zone is comfortable, but unproductive.*

Figure 36. *A ten-point guide for the motivated student.*

I am aware, however, that each generation experiences its own uncertainties and challenges, and must create its own solutions and make its own mistakes, so you have the right to disregard all of this advice. But if any of it can contribute to your personal growth, encourage you to demand more of yourselves, or strengthen your confidence in your abilities, then this final lesson will have been worthwhile.

EPILOGUE

Fight for the things that you care about. But do it in a way that will lead others to join you.
Ruth Bader Ginsburg

In the previous chapters, I attempted to reflect on the topic I mentioned at the beginning, situating the university within the turbulent context of our time and summarizing my professional life. This final section, however, necessarily requires a different tone, focusing on the personal.

I cannot begin without expressing my gratitude to the many—so many—who have contributed to my being able to close this chapter with serenity today. Not only with satisfaction, but also with that more difficult-to-describe feeling I recently heard a good friend express at a similar event: "I leave at peace with myself." Not because I believe I have done anything extraordinary, but because I am convinced that I have tried, with varying degrees of success, to fulfil the responsibility I owed to my profession, my university, my students, and ultimately, to society.

During these years, I have had the opportunity to achieve most of my professional goals. I have taught thousands of undergraduate, master's, and doctoral students, to whom I have tried to impart the ideas that have shaped this discourse. Some of these doctoral students are now researchers in Europe and America, have obtained professorships and international recognition, and have proven to be what every professor aspires to be: better than I, extending, expanding, and improving the school that Enrique Alarcón founded, and which I, like so many other colleagues, have tried to maintain.

I have been able to freely research whatever has demanded it of me at any given time or whatever I have considered interesting and useful. In every subject, I have tried to learn from those around me, many of them also better than I, to contribute something, and always to broaden horizons, to learn other languages and ways of doing things.

I have had the opportunity to travel the world, to experience other cultures and other work environments, and to make unexpected, lifelong friends. This has allowed me to be open, humble, and receptive to other ways of thinking, prioritizing, and approaching life and problems.

I have come to understand that individual progress, and even group progress, is a necessary but not sufficient condition. One must be involved in the improvement of the institution, contributing at every moment, from whatever position one holds, to the improvement of the centre, the institute, the university, the community, or the country. This is what I have tried to do both at the School and outside of it. Perhaps the biggest flaw I see in my young colleagues is the selfishness of protecting their immediate group, forgetting the responsibility they have to the wider community.

I have been fortunate to have students who decided to embark on the adventure and face the risk of creating new companies, so I have tried to contribute to them to the best of my ability and knowledge. Furthermore, I was incredibly lucky to participate from the beginning in a unique experiment in private research in Spain, Abengoa Research. There, I not only learned and grew personally and professionally, but I also reaffirmed my belief that when many, and very good, people row in the same direction, great goals are achieved. Finally, I have always tried to help society in the roles I have held, whether on committees or evaluation boards, advisory boards, in academies, or other institutions.

Obviously, many things remain undone, some of them still in my computer files. I am also aware that I didn't always make the best decisions, that I was stubborn in some of them, and that I didn't meet everyone's expectations. I humbly apologize to those who suffered from these mistakes. However, you can rest assured that I always acted believing that each decision was in everyone's best interest, and ultimately, also in the best interest of those affected.

I am fully aware that I have only been repaying a small part of all that others have done for me. Among those who decisively influenced my training, I want to remember first and foremost my mentor, Enrique Alarcón, a leading figure in Spanish engineering and the driving force behind a school to which I am honored to belong. From him, I learned rigor in problem-solving, the importance of never losing sight of the link between theoretical research and its practical application, profound respect for academic tradition and explicit recognition of those who came before us, and generosity toward those who come after. But also something less tangible and perhaps more decisive: a thirst for knowledge. His example embodies the model of professor I have tried to emulate ever since, aware that the result would necessarily be imperfect.

Later, during my time at Stanford University, I met Juan Carlos Simó. My subsequent dedication to nonlinear solid mechanics owes much to those conversations and to his approach to scientific research. With him, I understood that equations are not merely a technical language, but a way of thinking with precision, changing my understanding of science.

To these influences was added the discovery of the formal beauty of mathematics. Many professors contributed to awakening and nurturing this sensitivity: Juan García, at the Séneca Institute in Córdoba; Román Riaza, at the School of Industrial Engineers in Madrid; Robert Kohn, at the Courant Institute in New York; Jerry Marsden, at Stanford; and later, Ray Ogden. Each, at different times and with different emphases, contributed to consolidating a conviction that has never left me: mathematical elegance is not an aesthetic luxury, but a form of intellectual clarity.

Another essential element of any academic career, and in my case it has been, is the good fortune of working with colleagues and collaborators of enormous talent. I have had the privilege of sharing long discussions and reflections with colleagues and friends, from whose intelligence and rigor I have learned as much as, or even more than, from any treatise. Antonio Martín, José and Jaime Domínguez, Federico París, Rafael Picón, Francisco García Benítez, Alfonso Fernández Canteli, and many others have made decisive contributions to my understanding of solid and computational mechanics. Some of them are here today, others couldn't make it, and several are no longer with us, but their influence remains in every shared idea and every conversation that helped broaden my understanding of problems.

Secondly—but no less importantly—are my colleagues in the Department of Continuum Mechanics and Structural Theory at the University of Zaragoza. I have shared most of my professional life with them. Many were initially students and, over time, became colleagues and mentors in various ways. I can't mention them all, but they know that my gratitude to each of them is deep and sincere. Of course, I want to give special thanks to all those who made this event possible and made me so happy: Elías, Iñaki, Fany, Miguel Ángel, Begoña, and everyone else.

To my students at all levels, especially the doctoral students. There are many of them, and a significant number coincide with those mentioned above. The university has this beautiful characteristic: the professor-student relationship can transform, over the years, into a collaboration between equals. Besides those already mentioned, I want to acknowledge Sagrario Gómez in Madrid and Luis Gracia in Zaragoza in the first two, and Jaco Ayensa and Marina Pérez, who round out the list (for now).

As I believe has become clear, over these decades, my university work has occupied a very significant part of my time, my energy, and, on more than a few occasions, my concerns. Research, teaching, university administration, and projects shared with colleagues in different parts of the world have required travel, long days, and unavoidable absences.

I therefore want to thank everyone who, at one time or another, supported and encouraged me. I have friends all over the world; many of them were able to come today, and others weren't, but I am equally grateful for their friendship, especially those who have spoken. Among the many others I can't mention in such a short time, and I hope they will forgive me, from Abengoa Research, I thank Juan Luis, Juan Pablo, Manuel, Antonio, Jesús, Fernando, and Shahzada, representing all those with whom I was fortunate enough to work and learn, and with whom, including their wives, Estrella, Carmen, Eva, Adriana, and María, I continue to enjoy their friendship. Likewise, I thank the many friends in the healthcare field with whom I have worked: Daniel Palanca, Emilia Barrot, Ángel Ginel, Felipe Prósper, Ángel Borque, and Ángel Lanas, among many others. To my colleagues at CIBER, and to my friends from the Spanish and European Academies of Engineering and the Academy of Sciences of Zaragoza, represented here today by Jaime Domínguez, a friend of so many years, Paco Herrera, José Manuel Torralba, Antonio Huerta, J.N. Reddy, and Antonio Elipe, from whom I learn so much. To Iñaki and Luis, who welcomed me back to university. To my friends from the School, especially Manuel Silva, Rafael Navarro, and Rafael Bilbao, who have passed away. Finally, to all the institutions where I have been fortunate enough to work and which allowed me to freely develop ambitious projects, especially my University of Zaragoza. I'm sure I'm forgetting many but know that I carry them all in my heart.

To my late parents, to my siblings Emilio, Marisa, and Lola, who are with me today, to my closest friends, Julián and Esperanza, Antonio and Elena, Luis and Blanca, Javier and María José. Thanks to Alberto, a wonderful son, critical of me and society, restless, generous, and supportive, of whom, although I don't tell him often enough, I am very proud. Together with his wife, my dear Ayelén, they have given me the most precious thing a person can have in their later years: the unconditional and innocent love of my granddaughter Vega, who brightens my life and renews my hope every day.

Finally, none of this would have been possible without the silent, constant, and generous support of the person who has shared this entire journey with me since we were practically children: my wife, Conchi. She has been present at every stage of this path, without seeking the limelight, sacrificing her own professional goals, and maintaining the balance between personal and academic life. Those of us who have dedicated our lives to academia know that this profession never ends when we leave the office or the laboratory; ideas, problems, and worries accompany us home, on trips, even during moments that should be for rest. Conchi has navigated all of this with an admirable blend of patience, intelligence, and generosity. If I can look back today with the serenity of having travelled a path full of meaning, it is largely thanks to her. At the end of a career, one discovers something that often goes unnoticed: articles, projects, and awards are important, but they are not what truly matters. What truly matters are the people. And if there is one person without whom this story simply wouldn't have existed, it's you, Conchi.

Thank you all so much for joining me on this very special day.

REFERENCES

1. Eriksen, T.H. & Visentin, M. (2023) *Acceleration and Cultural Change: Dialogues from an Overheated World*. Springer Verlag. ISBN: 978-3031331015
2. Kelly, K. (2017) The Inevitable: *Understanding the 12 Technological Forces That Will Shape Our Future*. Penguin Publishing Group. ISBN: 978-0143110378
3. Susskind, D. (2024) Growth: A Reckoning. Allen Lane Ed. ISBN: 978-0241542309
4. Romer, P. M. (1990) Endogenous Technological Change. *Journal of Political Economy*, 98(5, Part 2), S71-S102.
5. Hassan, R. (2009) *Empires of Speed: Time and the Acceleration of Politics and Society*. Brill Academic Pub. ISBN: 978-9004175907
6. Hawthorne, J (2024) *The Age of Big Data: Harnessing Information for Insight and Impact*. RWG Publishing. ISBN-979-8330671236
7. Chayko, M. (2017) *Superconnected: The Internet, Digital Media, and Techno-Social Life*. SAGE Publications, Inc. ISBN: 978-1071805275
8. Talwar, R.; Wells, S.; Whittington, A. & Calle, H. (2018) *A Very Human Future: Enriching Humanity in a Digitized World*. Fast Future Publishing. ISBN: 978-1999931131
9. Brynjolfsson, E. & McAfee, A. (2016) *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*. W. W. Norton & Company. ISBN: 978-0393350647
10. Mollick, E. (2024) *Co-Intelligence: Living and Working with AI*. Portfolio. ISBN: 978-0593716717
11. Roco, M. C. & Bainbridge, W. S. (Eds.) (2010) *Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information*

Technology and Cognitive Science. Springer Verlag. ISBN: 978-9048162796

12. Kurzweil, R. (2001) *The Law of Accelerating Returns*. Published on KurzweilAI
13. Kurzweil, R. (2006) *The Singularity Is Near: When Humans Transcend Biology*. Penguin Publishing Group. ISBN: 978-0143037880
14. Twenge, J. M. (2017) *iGen: Why Today's Super-Connected Kids Are Growing Up Less Rebellious, More Tolerant, Less Happy--and Completely Unprepared for Adulthood--and What That Means for the Rest of Us*. Atria Books. ISBN: 978-1501152016
15. Sunstein, C. R. (2017) *#Republic: Divided Democracy in the Age of Social Media*. Princeton University Press. ISBN: 978-0691180908
16. Zuboff, S. (2019) *The Age of Surveillance Capitalism: The Fight for a Human Future at the New Frontier of Power*. Profile Books. ISBN: 978-1781256855
17. Noble, S. U. (2018) *Algorithms of Oppression: How Search Engines Reinforce Racism*. NYU Press. ISBN: 978-1479837243
18. Ford, M. (2015) *Rise of the Robots: Technology and the Threat of a Jobless Future*. Basic Books. ISBN: 978-0465059997
19. CITRINI & Shah, A. (2026) The 2028 global intelligence crisis. A Thought Exercise in Financial History, from the Future. Citrini Reports. https://www.citriniresearch.com/p/2028gic
20. Acemoglu, D. & Restrepo, P. (2019) Automation and New Tasks: How Technology Displaces and Reinstates Labor. *Journal of Economic Perspectives*, 33(2), 3–30
21. Standing, G. (2011) *The Precariat: The New Dangerous Class*. Bloomsbury Academic. ISBN: 978-1474294164
22. Bostrom, N. (2016) *Superintelligence: Paths, Dangers, Strategies*. Oxford University Press. ISBN: 978-0198739838

23. Chalmers, D. J. (2010) The Singularity: A Philosophical Analysis. *Journal of Consciousness Studies*, 17(9-10), 7–65
24. Scharre, P. (2018) *Army of None: Autonomous Weapons and the Future of War*. W. W. Norton & Company. ISBN: 978-0393608984
25. Gates, K.A. (2011) *Our Biometric Future: Facial Recognition Technology and the Culture of Surveillance*. New York University Press. ISBN: 978-0814732106
26. Hawley, J. (2021) *The Tyranny of Big Tech*. Regnery. ISBN: 978-1684512393
27. Harari, Y. N. (2017) *Homo Deus: A Brief History of Tomorrow*. Harper. ISBN: 978-0062464316
28. Möller, M. & Vuik, C. (2017) On the impact of quantum computing technology on future developments in high-performance scientific computing. *Ethics Inf Technol* 19, 253–269
29. Preskill, J. (2018) Quantum Computing in the NISQ era and beyond. *Quantum*, 2, 79
30. Drexler, E. (1987) *Engines of Creation: The Coming Era of Nanotechnology*. Knopf Doubleday Publishing Group. ISBN: 978-0385199735
31. Allhoff, F.; Lin, P.; Moor, J. & Weckert, J. (2007) *Nanoethics: The Ethical and Social Implications of Nanotechnology*. JE. ISBN: 978-0470084175
32. Church, G.M. & Regis, E. (2012) Regenesis: How Synthetic Biology Will Reinvent Nature and Ourselves. Basic Civitas Books. ISBN: 978-0465021758
33. Amodeli, D. (2024) *Machines of Loving Grace. How AI Could Transform the World for the Better.* https://www.darioamodei.com/essay/machines-of-loving-grace

34. Osterholm, M.T. & Olshaker, M. (2025) *The Big One: How We Must Prepare for Future Deadly Pandemics*. Little Brown and Company. ISBN: 978-0316258340
35. Sandel, M. J. (2007) *The Case Against Perfection: Ethics in the Age of Genetic Engineering*. Belknap Press. ISBN: 978-0674019270
36. Rose S. (2006) *The Future of the Brain: The Promise and Perils of Tomorrow's Neuroscience*. Oxford University Press. ISBN: 978-0195308938
37. Abu-Shawareb, H.; Acree, R.; Adams, P.; Adams, J.; Addis, B.; Aden, Adrian, P.; Afeyan, B.B. et al. (2024) Achievement of Target Gain Larger than Unity in an Inertial Fusion Experiment. *Phys. Rev. Lett.* 132, 065102.
38. IEA (2025), The Path to a New Era for Nuclear Energy, IEA, Paris https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy
39. Diamandis, P. H.; & Kotler, S. (2020) Abundance: The Future Is Better Than You Think. Simon & Schuster USA. ISBN: 978-1982109660
40. Ord, T. (2020) *The Precipice: Existential Risk and the Future of Humanity*. Hachette Books. ISBN: 978-0316484916
41. Huesemann, M. & Huesemann, J. (2011) *Techno-Fix: Why Technology Won't Save Us Or the Environment*. New Society Publishers. ISBN: 978-0865717046
42. Fisher, J.R. (2021) The Rise and Fall of the Human Empire. Editado por el autor. ISBN: 979-8764637532
43. Nah, A.M. (2020) *Protecting Human Rights Defenders* At Risk. Rotledge. ISBN: 978-1138392618
44. Arnell, N. (2015) *A Short Guide to Climate Change Risk*. Routledge. ISBN: 978-1409453529
45. Kolbert, E. (2014) *The Sixth Extinction: An Unnatural History*. Macmillan USA. ISBN: 978-0805092998

46. Ritchie, H. (2024) *Not the End of the World*. Vintage. ISBN: 978-1529931242
47. Gates, B. (2022) *How to Avoid a Climate Disaster.* Knopf Doubleday Publishing Group. ISBN: 978-0593081853
48. Bullock, J.B. et al. (eds.) (2023) *The Oxford Handbook of AI Governance*. Oxford Academic. ISBN: 978-0-19-754217-0.
49. Darwin, C. (1959) *On the Origin of Species*. London
50. Bowen, J.A. (2025) *Teaching with AI: A Practical Guide to a New Era of Human Learning*. Johns Hopkins University Press (2nd Ed.) ISBN: 978-1421453392
51. Ahmad, S. & Doblaré, M. (2026) Walking with the Lions: Pearls and Pitfalls of Mentoring (under revision)
52. Sandel, M. J. (2020) The Tyranny of Merit: What's Become of the Common Good? Farrar Straus & Giroux. ISBN: 978-0374289980
53. UNESCO. (2021) *La ciencia al servicio de la sociedad*. https://es.unesco.org/themes/cien- cia-al-servicio-sociedad
54. Bongaerts, J.C. (2022) The Humboldtian Model of Higher Education and its Significance for the European University on Responsible Consumption and Production. *Berg Huettenmaenn Monatsh* 167, 500–507
55. National Human Genome Research Institute (2003) *The Human Genome Project*. https://www.genome.gov/human-genome-project
56. EU Commision (2023), *Human Brain Project Flagship*. https://www.humanbrainproject.eu/en/
57. World Intellectual Property Organization. (2026) Innovation Capabilities Outlook 2026. ISBN: 978-92-805-3894-6 https://www.wipo.int/edocs/pubdocs/en/wipo-pub-1091-en-innovation-capabilities-outlook-2026.pdf

58. Bloom, N.; Jones, C.I.; Van Reenen, J. & Webb, M. (2020) Are Ideas Getting Harder to Find?. *American Economic Review*, 110(4):1104–44.
59. Klein, E. & Thompson, D. (2025) *Abundance: What Progress Takes.* Avid Reader Press. ISBN: 978-1668023488
60. Bhattacharya, J. & Packalen, M. (2020) Stagnation and scientific incentives. Working Paper 26752 Cambridge, MA: National Bureau of Economic Research. http://www.n-ber.org/papers/w26752
61. Acemoglu, D. (2002) Directed Technical Change. *The Review of Economic Studies*, 69(4), 781–809.
62. Gobierno de España. (2021) Estrategia Española de Ciencia, Tecnología e Innovación 2021-2027. https://http://www.ciencia.gob.es/InfoGeneralPortal/documento/e8183a4d-3164-4f30-ac5f-d75f1ad55059
62. Rodríguez-Navarro, A. (2022) *Cómo medir el éxito científico*. Aula Magna Proyecto Clave McGraw Hill. ISBN: 978-8419187413
63. ICREA (2025) ICREAMEMOIR2024. https://memoir.icrea.cat/
64. Medwar, P.B. (1980) *Advice to a Young Scientist*. Joanna Cotler Books. ISBN: 978-0063370067
65. Lawrence, P. A. (2016) The last 50 years: Mismeasurement and mismanagement are impeding scientific research. *Current Topics in Developmental Biology*, 116:617-631.
66. Rodríguez-Navarro, A. & Brito, R. (2023) The extreme upper tail of Japan's citation distribution reveals its research success. arXiv:2201.04031. https://doi.org/10.48550/arXiv.2201.04031
67. Herranz, N. & Ruiz-Castillo, J. (2011) The end of the European Paradox. Centre for Economic Policy and Research. file:///Users/manueldoblare/Downloads/ssrn-1976016-1.pdf
68. World Intellectual Property Organization (WIPO) (2023) Global Innovation Index. https://www.wipo.int/en/web/global-innovation-index/2023/index

69. Snow, C.P. (1959) *The Two Cultures and the Scientific Revolution*. Cambridge University Press.
70. Pierre, J. (2025) *False: How Mistrust, Disinformation, and Motivated Reasoning Make Us Believe Things that Aren't True*. OUP USA. ISBN: 978-0197765272
71. Robert, J.; Faris, R. & Roberts, H. (2018) *Network Propaganda: Manipulation, Disinformation, and Radicalization in American Politics*. OUP USA. ISBN: 978-0190923631
72. Doblaré, M. (2008) Retos y oportunidades de la investigación transdisciplinar. Reflexión sobre el papel de la mecánica de materiales en biomedicine. Real Academia de Ingeniería. https://www.raing.es/discursoingreso/retos-y-oportunidades-de-la-investigacion-transdisciplinar-reflexion-sobre-el-papel-de-la-mecanica-de-materiales-en-biomedicina/
73. Nicolescu B. (1998) Gödelian *Aspects of Nature and Knowledge*. Bulletin Interactif du Centre International de Recherches et Études transdisciplinaires. http://perso.club-internet.fr/nicol/ciret/
74. Gibbons, M.; Limoges, C.; Nowotny, H.; Schwartzman, S.; Scott, P. & Trow, M. (1994) *The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies*. SAGE Publications Ltd. ISBN: 978-0803977938
75. Doblare, M. & Garcia-Aznar J.M. (2002) Anisotropic bone remodelling model based on a continuum damage-repair theory. *Journal of Biomechanics*, 35(1):1–17
76. Rothschild, J.L & Mancinelli R.L. (2001) Life in extreme environments. *Nature*, 409(6823):1092–1101, 2001.
77. Tu, Y & Rappel W-J. (2018) Adaptation in living systems. *Annual review of condensed matter physics,* 9(1):183–205

78. Abbas A.K.; Lichtman, A.H. & Pillai, S. (2021) *Cellular and molecular immunology*. Elsevier (10th edition), ISBN 978-0323479783
79. Futuyma, D.J. & Kirkpatirck, M. (2017) *Evolution*. Sinauer Associates, ISBN 978-1605356051
80. Billman, G.E. (2020) Homeostasis: the underappreciated and often ignored central organizing principle of physiology. *Frontiers in Physiology*, 11:200.
81. Jaenisch, R. & Bird, A. (2003) Epigenetic regulation of gene expression: how the genome integrates intrinsic and environmental signals. *Nature Genetics*, 33(3s):245–254.
82. Cannon, W.B. (1932) *The wisdom of the body*. Norton,
83. Angilletta, M.J. Jr; Youngblood, J.P.; Neel, L.K. & Vanden-Brooks, J.M. (2019) The neuroscience of adaptive thermoregulation. *Neuroscience Letters*, 112:103491.
84. Frost, H.M. (2003) Bone's mechanostat: A 2003 update. *The anatomical record. Part A, Discoveries in Molecular, Cellular, and Evolutionary Biology*, 275A:1081–1101.
85. Frost, H.M. (1964) Dynamics of bone remodelling. In *Bone remodeling*, 315–333.
86. Riggs, D.S. (1976) *Control theory and physiological feedback mechanisms*. RE Krieger Pub Co. ISBN 9780882753584
87. Zhou, K. & Doyle, J.C. (1998) *Essentials of robust control*, volume 104. Prentice Hall, ISBN 978-0135258330
88. Allis, C.D.; Jenuwein, T.; Reinberg, D. & Caparros, M.L. (eds.) (2007) *Epigenetics*. Cold Spring Harbor Laboratory Press, ISBN 978-0879697242
89. Lacal, I. & Ventura, R. (2018) Epigenetic inheritance: concepts, mechanisms and perspectives. *Frontiers in Molecular Neuroscience*, 11:292.

90. Coleman, B. & Gurtin, E. (1967) Thermodynamics with internal state variables. *Journal of Chemistry and Physics*, 47:597–613.
91. Simo, J.C. & Hughes, T.J.R. (1998) *Computational inelasticity*. Springer, ISBN 978-0387975207
92. Lemaitre, J. (1985) A continuous damage mechanics model for ductile fracture. *Journal of Engineering Materials and Technology*, 107:83–89.
93. Doblaré, M.;Pérez-Aliacar, M.; Ayensa-Jiménez, J. & Ashrafi, M. (2026) A phenomenological mathematical framework to model homeostasis as a robust, adaptive control system. Similarities with continuum nonlinear physics with internal variables, Mechanics of Materials, 213, 105546.
94. Bray, F.; Laversanne, M.; Sung, H.; Ferlay, J.; Siegel, R.L.; Soerjomataram, I. & Jemal, A. (2024) *Global cancer statistics 2022: Globoscan estimates of incidence and mortality worldwide for 36 cancers in 185 countries. CA: a cancer journal for clinicians*, 74(3):229–263
95. Batash, R.; Asna, N.; Schaffer, P.; Francis, M. & Schaffer, M. (2017) Glioblastoma multiforme, diagnosis and treatment; recent literature review. *Current medicinal chemistry*, 24(27):3002–3009.
96. Grochans, S.; Cybulska, A.M.; Siminska, D.; Korbecki, J.; Kojder, K.;;Chlubek, D. & Baranowska-Bosiacka, I. (2022) Epidemiology of glioblastoma multiforme–literature review. *Cancers*, 14(10):2412
97. Stankovic, T.; Randelovic, T.; Dragoj, M.; Stojkovic Buric, S.; Fernández, L.; Ochoa, I.; Pérez-García, V.M. & Pesic, M. (2021) In vitro biomimetic models for glioblastoma-a promising tool for drug response studies. *Drug Resistance Updates*, 55:100753
98. Jiapaer, S.; Furuta, T.; Tanaka, S.; Kitabayashi, T. & Nakada, M. (2018) Potential strategies overcoming the temozolomide resistance for glioblastoma. *Neurologia medico-chirurgica*, 58(10):405–421.

99. Oike, T.; Suzuki, Y.; Sugawara, K.; Shirai, K.; Noda, S.; Tamaki, T.; Nagaishi, M.; Yokoo, H.; Nakazato, Y & and Nakano, T. (2013) Radiotherapy plus concomitant adjuvant temozolomide for glioblastoma: Japanese mono-institutional results. *PLoS One*, 8(11):e78943.
100. Stupp, R.; Mason, W.P.; Van Den Bent, M.J.; Weller, M.; Fisher, B.; Taphoorn, M.J.B.; Belanger, K.; Brandes, A.A.; Marosi, C.; Bogdahn, U. et al. (2005) Radiotherapy plus concomitant and adjuvant temozolomide for glioblastoma. *New England journal of medicine*, 352(10):987–996.
101. Ali, M.D.Y.; Oliva, C.R.; Noman, A.S.M.; Allen, B.G.; Goswami, P.C.; Zakharia, Y.; Monga, V.; Spitz, D.R.; Buatti, J.M. & Griguer, C.E. (2020) Radioresistance in glioblastoma and the development of radiosensitizers. *Cancers*, 12(9):251.
102. Singh, N.; Miner, A.; Hennis, L. & Mittal, S. (2021) Mechanisms of temozolomide resistance in glioblastoma-a comprehensive review. *Cancer drug resistance*, 4(1):17.
103. Duncan, E.J. Gluckman, P.D. & Dearden, P.K. (2014) Epigenetics, plasticity, and evolution: How do we link epigenetic change to phenotype? Jou*rnal of Experimental Zoology Part B: Molecular and Developmental Evolution*, 322(4):208–220.
104. Hanahan, D. (2022) Hallmarks of cancer: new dimensions. *Cancer discovery*, 12(1): 31–46.
105. Aasland, D.; Gotzinger, L.; Hauck, L.; Berte, N.; Meyer, J.; Effenberger, M.; Schneider, S.; Reuber, E.E.; Roos, W.P.; Tomicic, M.T. et al. (2019) Temozolomide induces senescence and repression of dna repair pathways in glioblastoma cells via activation of atr–chk1, p21, and nf-ϰb. *Cancer research*, 79(1):99–113, 2
106. Gunther, W.; Pawlak, E.; Damasceno, R.; Arnold, H. & Terzis, A.J. (2003) Temozolomide induces apoptosis and senescence in glioma

cells cultured as multicellular spheroids. *British journal of cancer*, 88(3):463–469.

107. Lee, S.Y. (2016) Temozolomide resistance in glioblastoma multiforme. *Genes & diseases*, 3(3):198–210.

108. Silva, A.O.; Dalsin, E.; Onzi, G.R.; Filippi-Chiela, E.C. & Lenz, G. (2016) The regrowth kinetic of the surviving population is independent of acute and chronic responses to temozolomide in glioblastoma cell lines. *Experimental Cell* Research, 348(2):177–183.
109. Tomar, M.S.; Kumar, A.; Srivastava, C. & and Shrivastava. A. (2021) Elucidating the mechanisms of temozolomide resistance in gliomas and the strategies to overcome the resistance. Biochimica et Biophysica Acta (BBA)-*Reviews on Cancer*, 1876(2):188616.
110. Nath S. & Devi, G.R. (2016) Three-dimensional culture systems in cancer research: Focus on tumor spheroid model. *Pharmacology & therapeutics*, 163:94–108.
111. Nunes, A.S.; Barros, A.S.; Costa, E.C.; Moreira, A.F. & Correia, I.J. (2019) 3d tumor spheroids as in vitro models to mimic in vivo human solid tumors resistance to therapeutic drugs. *Biotechnology and bioengineering*, 116(1):206–226.
112. Pérez-Aliacar, M.; Ayensa-Jiménez, J. & Doblaré, M. (2023) Modelling cell adaptation using internal variables: Accounting for cell plasticity in continuum mathematical biology. *Computers in Biology and Medicine*, 164:107291.
113. Gilbert, M.R.; Wang, M. Aldape, K.D.; Stupp, R.; Hegi, M.E.; Jaeckle, K.A.; Armstrong, T.S.; Wefel, J.S.; Won, M.; Blumenthal, D.T. et al. (2013) Dose-dense temozolomide for newly diagnosed glioblastoma: a randomized phase iii clinical trial. *Journal of clinical oncology*, 31(32):4085–4091.

114. Pinker, S. (2018) Enlightenment Now: The Case for Reason, Science, Humanism, and Progress. Viking. ISBN: 978-0525427575

115. Freitas, R. A.; Jr. (1998) Exploratory Design in Medical Nanotechnology: A Artificial Mechanical Erythrocyte. *Artificial Cells, Blood Substitutes, and Immobilization Biotechnology*, 26(4), 411–430.

Universidad Zaragoza

Real Academia de Ingeniería