



Does anybody really know what time it is? From biological age to biological time

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Abstract During his celebrated 1922 debate with Bergson, Einstein famously proclaimed: “the time of the philosopher does not exist, there remains only a psychological time that differs from the physicist’s.” Einstein’s dictum, I maintain, has been metabolized by the natural sciences, which typically presuppose, more or less explicitly, the existence of a single, univocal, temporal substratum, ultimately determined by physics. This reductionistic assumption pervades much biological and biomedical practice. The *chronological age* allotted to individuals is conceived as an objective quantity, allowing one to straightforwardly assign and compare the *biological age* of organisms. This essay argues that the standard practice of assessing the age and aging of organisms against the backdrop of a physical conception of time is problematic. This becomes especially evident in light of recent discoveries of various levels of senescence underlying the development of individual organisms—a phenomenon known as ‘age mosaicism.’ The bottom line is that the study of age and aging requires a biological conception of time, as opposed to a physical one. Einstein clearly wasn’t wrong about his operationalization of time in relativity theory. Still time may be less monolithic than he surmised.

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1 Einstein's dictum

On April 6, 1922, in front of the eminent *Société française de philosophie*, the great physicist Albert Einstein proclaimed: 'Il n'y a donc pas un temps des philosophes.' There is no such thing as the philosophers' concept of time. What did Einstein mean? Why was this widely-cited quote so incendiary?

The context of Einstein's statement was his celebrated debate with the French philosopher Henri Bergson, which pitted against each other two of the most influential intellectuals of their generations. Reacting to Einstein's groundbreaking discoveries, Bergson had argued that time could not—and should not—be characterized exclusively through the lens of physics. Time cannot be reduced to a purely scientific concept. There is more to time itself than science can wager. To be clear, this is not to maintain that theoretical physics is guilty of any mistake or miscalculation. Bergson's point is rather that the concept of time, objectively construed, has a further, 'philosophical dimension,' which transcends what science can capture, analyze, or explain.

Einstein vehemently disagreed. From his perspective, there are two, and only two valid ways of understanding time. A physical one and a psychological one. Elaborating on this dichotomy, Einstein insisted that his own definition of time, exhaustively articulated throughout the theory of relativity, has a clear and objective meaning. What is left out of the relativistic conception of time is the subjective, human experience of time itself, which falls under the purview of psychology. Bergson's notion belongs neatly in neither category. Philosophical time is explicitly taken to lie outside of the domain of physics. But, at the same time, it does not coincide with the psychological characterization either. As such, it has no legitimate claim to existence. It is in this sense that Il 'n'y a donc pas un temps des philosophes.'

Bergson's full-fledged development of his esoteric 'philosophical' conception of time spanned various publications over several years. His debate with Einstein sparked longstanding and substantive discussions—for an excellent reconstruction of the exchange and its aftermath see Canales (2015); for an analysis of the psychological dimension of time, together with its implications for age and aging, see Baars (2007a) and van der Meer (2007). A comprehensive overview of either topic transcends my interest and professional competence. The relevant point, for our present purposes, is that, whereas Bergson viewed time as irreducible to physics, Einstein disagreed.

These considerations raise a deceptively simple question. Einstein explicitly acknowledged that time does not have a single, univocal, objective physical meaning. Time also has a subjective, psychological component. If Einstein was perfectly willing to accept a psychological notion of time, running parallel to his physical operationalization, why was he so adamantly opposed to Bergson's *philosophical* characterization? The answer, or so it seems to me, is that Einstein's psychological time is not, and was never meant to be, understood as objectively as its physical counterpart. Events which have roughly the same duration are frequently experienced differently by human beings. As anyone who has struggled

through a boring performance can attest, some hours feel much longer than others. This much is indisputable. But Bergson's philosophical conception went beyond this platitude. Philosophical time threatened to become a competitor, an irreducible alternative to physical time. And, this, Einstein felt, was unacceptable.

Be that as it may, the debate was won by Einstein by technical knockout. Einstein is nowadays celebrated as a hero of contemporary physics and, indeed, science at large. Bergson is often—and all too often—relegated to dusty history of philosophy textbooks. Philosophical time has turned into a non-issue, and so is any surrogate notion. This outcome is hardly inconsequential. This article draws attention to some of the momentous implications that Einstein's stance has had on the scientific community broadly construed and, especially, on current gerontology and various cognate fields.

The chief aim of this essay is to examine how this timeworn conception of time—what I call 'Einstein's dictum'—pervades the contemporary study of age and aging across the sciences, in general, and the life sciences, in particular. Here is the overarching structure and plan for the ensuing pages. Section 2 kicks off and sets the stage by drawing a well-known distinction between two concepts of age—chronological age versus biological age—and discussing their relation with time. Next, Sect. 3 discusses the operationalization of age, aging, and time in contemporary biological discourse, and argues that recent discoveries concerning 'age mosaicism' undermine the intuitive idea that we can meaningfully talk about the biological age of an entire organism. Section 4 sketches a solution to resolve the tension, namely, to recognize that any bona fide biological age needs to be founded upon a biological conception of time. This, I shall argue, entails relaxing physicalist strictures and, specifically, dropping the presupposition that time is exclusively a physical construct. Section 5 concludes by outlining some general implications of the present proposal.

Before moving on, an important clarification is in order. Like Bergson, in rejecting what I call 'Einstein's dictum,' I am hardly suggesting that physics is mistaken or incomplete. My proposal is that studies of age and aging require a robust biological notion of time. Clearly, any temporality worth its salt must be broadly compatible with the theory of relativity. Nevertheless, I do surmise that Einstein's swift dismissal of any conception of time that is neither physical nor psychological may have been too rash.

2 Two concepts of age

The previous section introduced and briefly motivated Einstein's dictum. Simply put, this can be presented, in a slogan, as the tenet that there is no such thing as the time of the philosopher. Time, Einstein maintained, only has two aspects: an objective physical one and a subjective psychological one. I advanced my claim that this reductionist assumption has shaped, and continues to influence the way age and aging are conceived in contemporary biological and biomedical studies. We now need to substantiate this thesis.

The present section introduces an influential distinction between two concepts of age—chronological versus biological (Baars 2007b)—and discusses their relation with time. This preliminary setup will lay the groundwork for my main argument, which spans the remainder of the essay. Specifically, Sect. 3 discusses the operationalization of age, aging, and time, and presents some challenges for the intuitive application of biological age to entire organisms. Section 4 argues that, in order to retain the biological age of organisms, we need to devise a ‘biological’ characterization of time. Biological age presupposes biological time, a proposition which, it should be clear, is flatly at odds with Einstein’s dictum. But now I’m already getting ahead of myself...

In common parlance, ‘age’ is routinely defined as the length of an existence, extending from a specific beginning to a particular point in its future. The main idea can be illustrated with simple examples. Napoleon died at the age of fifty-one. *Sequoia sempervirens*, commonly known as coast redwood trees, can live to an age of over two thousand years. W.A. Mozart started composing music at the tender age of five. In all these cases, ‘age’ corresponds to what is frequently called *chronological age*. This refers to a precise lapse of time: the number of measurable temporal units—seconds, days, years...—elapsing from birth to some event of interest, in the past, present, or future. Correspondingly, aging is understood as the inevitable passage of time. It should be evident that, from this standpoint, both age and aging, understood chronologically, can be straightforwardly reduced to time. Age is nothing over and above a stretch of time that can be used to date and measure the lifespan of entities. I intentionally say ‘entities’ as opposed to ‘organisms’ because chronological age, thus conceived, can also be applied to inanimate objects, as when we talk about the age of the pyramids, your grandfather’s old gramophone, or my collection of single-malt whisky. Obviously, in such cases, the starting point is not birth, but creation, manufacturing date. In short, chronological aging is the subjection of an entity to age, the inexorable passage of time.

In addition to chronological age, there is also a subtly different conception, which keeps the notions of age and aging separate from elapsed time. This second kind of age is typically called *biological age*, although I find this nomenclature misleading for the simple reason that, as we shall promptly see, like its chronological counterpart, it applies to biological and non-biological entities alike. Be that as it may, biological age—I shall stick with traditional terminology—characterizes age as the effect of time.

The rationale for drawing a sharp distinction between chronological and biological conceptions of age and aging is fairly straightforward. Two organisms or objects may have spent an identical amount of time in this vale of tears we call Earth, while being affected to a different degree. To illustrate, the movies *Star Wars: A New Hope* and *Saturday Night Fever* both came out in 1977. Do they have the same age? Well, it depends. If age is intended chronologically, then they clearly do, as they were released in the same year. But this need not hold if age is viewed ‘biologically,’ as the effect of time. After all, one could maintain, the two movies have aged quite differently, in the sense that one feels fresher, more modern, and resembles more contemporary productions. Similarly, celebrities Celine Dion and Will Smith were both born in 1968. Do they have the same age? Again,

yes, chronologically speaking. But, from a biological standpoint, it doesn't follow that they have aged in exactly the same way. This passage versus effect of time shift can be seen most clearly in the case of twins which, by definition, are virtually identical in time-passage, but not necessarily with respect to time-effect.

In short, talk of the 'age' and 'aging' of entities, as it pertains to both common parlance and more scientific contexts, is ambiguous. On the first conception, chronological age is, essentially, the passage of time. On a second reading, biological age corresponds to the effect that time has on systems, of both organic and inorganic kind. What can we do to minimize confusion?

In order avoid conflation and keep these meanings distinct, it was once common to employ the term 'senescence' to refer to the process of biological age—age and aging *qua* effect of time—while reserving the terms 'age' and 'aging' *simpliciter* for chronological age, understood as the passing of time (Medawar 1981b). Nevertheless, 'senescence' and cognate notions have become somewhat obsolete, in part, I suspect, because of its less-than-flattering connotations. Also, aging begins long before senescence.

Nowadays, it is more typical to employ the substantive 'age' as synonymous with chronological age (echoing Blink 182 and Maung (2021), 'what's my age again?'), while reserving the verbal phrase 'aging' for the biological process whereby entities are affected by time ('I can't help noticing how well you've aged'; 'you look younger than your age'). Incidentally, languages other than English draw the distinction in question more sharply, by maintaining different nouns, along the basic age versus senescence lines. In Italian, the difference is expressed by 'età' versus 'invecchiamento' and there are corresponding hues in French ('âge' vs. 'vieillesse'), Spanish ('edad' vs. 'envejecimiento'), and German ('Alter' vs. 'Altern').

None of these linguistic conventions strike me as ideal, or fully satisfactory. As noted above, the label 'biological aging' misleadingly suggests that the concept only applies to organisms. 'Senescence' carries over negative associations with decrease in function. And 'age' and 'aging' appear to be orthogonal to the distinction under scrutiny. Both age and the process of aging can be applied to either the passing of time or the its effect on the system. In what follows, I shall stick to the 'chronological age versus biological age' convention. But, what is crucial for my argument is that these concepts remains clearly distinct, regardless of the choice of nomenclature.

Keeping these considerations in mind, we can rephrase our central question along the following lines: what is the relation between *chronological age*, *biological age*, and *time*? Intuitively, chronological age can be straightforwardly reduced to a specific lapse of time. The interplay between time and biological age, in contrast, is subtler, more complex. Note that biological age is not completely independent of time. The effects of time on an individual depend, in no small part, on how long they have been around. But clearly, biological aging—the effect of time—can't be straightforwardly reduced to time, on pain of contradiction. It would make no sense to claim that age is time elapsed since birth, while two objects that have been around the same amount of time have aged differently. Biological age, thus construed, reflects not merely the passage of time, but how entities are affected by its ticking. In sum, while there is more to biological age than the passing of time, it is not completely

independent of time either. With all this in mind, let's ask once again: what is the connection between biological age and time?

The key to this question is the observation that time becomes the objective substrate against which the process of biological aging can be quantified objectively. Allow me to elaborate. In order to measure and assess the process of biological aging across different individuals, we need some common denominator. This basic scale is provided by time. Suppose that we are trying to determine the biological age of an individual or compare the aging of various individuals. To get the inquiry off the ground, we first need to know how long these entities have been around. That is, to study the biological aging of an individual or group thereof, we first need to know their chronological age. Are we comparing people who belong to the same age group? It is only against this backdrop that the question of biological aging begins to make sense. *Chronological age*—passing of time—is the common factor that allows one to compare, contrast, and study *biological age*.

We are now in a position to see the connection to Einstein's dictum. The relation between chronological and biological age—as it is routinely conceived—is very much analogous to the relation between physical and psychological time, which emerged in the context of Einstein's debate with Bergson. As mentioned at the outset, Einstein vehemently rejected a 'Bergsonian' self-standing, objective, philosophical conception of time. Nevertheless, he was perfectly content with a subjective, psychological notion. The reason for this, I surmised, is that the psychological notion of time was never meant to be something over and above the underlying physical substratum. Clearly, it is perfectly meaningful to ask whether the two hours I spent watching the game *felt* shorter than the two hours it took me to file my taxes. Still, the comparison between the two events only makes sense against the bedrock of an objective notion of time, which provides a common measure bringing together the two experiences. Given that the game and my CPR appointment had objectively the same duration, two hours, did they feel subjectively different? Bergson's philosophical conception of time, in contrast, appears to be very different in nature. It is explicitly not meant to be understood in relation to physical time. On the contrary, it has a distinctive, autonomous, and independent status. It is quite possible to talk about time in 'Bergsonian' terms, without presupposing a physical bedrock notion at all. Indeed, philosophical time is introduced because, according to Bergson, there is more to time, objectively construed, than what physicists have to say about it. This is what Einstein found deeply unacceptable.

The interplay between age, aging, and time has been understood along analogous lines. Chronological age is elapsed time from birth. Biological age, in turn, captures how organisms and objects are individually affected by the objective passing of time. It should now be clear in what sense Einstein's dictum has permeated the scientific worldview at large. Concepts such as biological age should be characterized, in a reductionist fashion, against the backdrop of physical concepts such as time, or notions, like chronological age, that can be more or less straightforwardly reduced to physical time.

Is this hypothesis acceptable? Some readers might rejoin that, on a weak reading, the objective grounding of concepts from biology and other so-called 'special sciences'—fields other than fundamental physics—promotes a healthy materialism, a

reductionist agenda, and the unity of science. A thorough discussion of these core philosophical questions lies well beyond the scope of this work. My present goal, much more modestly, is to show that a physicalist characterization of biological age, prescribed by Einstein's dictum, is strikingly difficult to reconcile with current biomedical discoveries.

3 Operationalizing age, aging, and time

The previous section focused on the relation between age, aging, and time. Specifically, I tried to disambiguate common parlance by drawing an explicit wedge between two related, albeit distinct concepts. The first one, *chronological age* is a direct measure of time. As the passage of time, chronological age can be straightforwardly defined as elapsed time in the lifespan of an organism. In contrast, the second notion, *biological age*, reflects how individual or population-specific development is affected by the passing of time. Both conceptions of age, chronological and biological, I suggested, are typically measured against the backdrop of a physical conception of time, an assumption that I dubbed 'Einstein's dictum,' after the scientist's remarks in the context of his influential debate with Bergson on the nature of time. The questions now before us are: how does Einstein's dictum fit into the contemporary study of aging? Is the hypothesis plausible? The present section shows how recent discoveries concerning the biomedical conception of aging are difficult to square with the assumption of age measured directly against a backdrop of time. Section 4 sketches a solution: a biological conception of age, not directly reducible to any notion of physical time.

Let's begin with some general methodological remarks. For any concept whatsoever to be approached from a scientific standpoint, it must be *operationalized*, that is, it must be made quantifiable. Age, aging, and time are no exception. How do we operationalize these notions? One of Einstein's great contributions to modern physics—and science in general—was to show how this could be done for the concept of time via simultaneity. As Bridgman (1927, pp. 7–8) eloquently puts it in his classic treatise:

Before Einstein, the concept of simultaneity was defined in terms of properties. It was a property of two events, when described with respect to their relation in time, that one event was either before the other, or after it, or simultaneous with it. Simultaneity was a property of two events alone and nothing else, either two events were simultaneous or they were not. (...) Einstein now subjected the concept of simultaneity to a critique, which consisted essentially in showing that the operations which enable two events to be described as simultaneous involve measurements on the two events made by an observer, so that 'simultaneity' is, therefore, not an absolute property of the two events and nothing else, but also involve the relation of the events to an observer.

This was an integral part of Einstein's operationalization of time, which provided a rigorous physical treatment. Could something analogous be done with respect to age? Can we provide a viable, testable biomedical definition?

The case of chronological age is straightforward. Since chronological age corresponds to elapsed time since birth, it can be effectively operationalized by measuring how much time has passed since the organisms' come-to-being. To be sure, vagueness may question the location of the exact point in time where we should count an organism as 'born'—a thorny issue triggering notoriously heated bioethical debates. Still, if we adopt a relatively coarse-grained scale, the operationalization of chronological age piggy-backs on the measurement of time, defined as purely physical quantity.

Biological age, in contrast, is much more complex. Knowing that an organism is x years (months, weeks, or days) in age is a necessary piece of information for determining how the organism in question has aged in some specific interval of time. Nevertheless, it is hardly sufficient. As noted in Sect. 2, two individuals may easily have the same age without having aged in exactly the same way. How do we operationalize the biological aging process of an organism? How do we quantify it by assigning it some meaningful numerical value that allows one to compare and contrast it with other organisms, belonging to various different age-groups, populations, and even species?

The first step towards answering this question is figuring out the *biological units of age*. In other words, what are the entities that age and undergo aging? At first blush, this question may raise more than a few eyebrows. Is the answer not obvious? Such basic units are *organisms*. From this standpoint, one first keeps track of the age of an organism O_7 . Next, we determine how organism O_7 has aged. By operationalizing—that is, quantifying—this process, one is able to compare it with another organism O_9 or even a general contrast class $\{O_1, \dots, O_n\}$. Note how, from this standpoint, Einstein's dictum makes perfect sense. Chronological age is elapsed time since birth, and biological age captures the effect of time on the organism. Furthermore, the underlying rationale is quite simple. All parts of an organism—say, hands, liver, and brain—have exactly the same chronological age, as they were born simultaneously. Consequently, we can directly compare their biological age. But are things really this simple? Does this withstand serious scrutiny?

Over the last few decades, the assumption that organisms are uniform in chronological age has come under fire. The problem, succinctly put, is that each and every organism encompasses a plethora of independent units of age, an idea known as *age mosaicism*. To illustrate, in a recent article, Arrojo e Drigo et al. (2019) discuss a series of experiments aimed at measuring the age of cells and proteins in mice using high-resolution isotope imaging. The striking results suggest that adult mouse organs are mosaics of cells differing radically in chronological age. For instance, the liver, an organ known to have a high cellular turnover, contains cells as old as the animal itself. Cilia, in contrast, have differentially aged structural protein components.

Experimental technicalities aside, the conceptual point is plain. The lifespan of terminally differentiated cells varies drastically across organs and tissues, let alone within the entire organism. Expected longevity may range from three to four days, in the case of epithelial intestinal cells, to the entire lifespan of the animal, as with several neurons, cardiomyocytes, and all inner ear hair cells. How it is that some of these long-lived cells are capable of maintaining functional integrity over several decades remains poorly understood. Still, there is strong evidence that these cells are

never replaced. In short, consider human beings and other species that can live over a century. We have cells as old as the organisms itself, which must function properly for the entire life, and cells that get routinely replaced in a matter of days. Because of these striking differences in the chronological age of cells, not merely within the same organism, but the same organ, Arrojo e Drigo et al. (2019, p. 343) “propose that age mosaicism across multiple scales is a fundamental principle of adult cell tissue, cell, and protein complex organization.”

The fascinating details of age mosaicism lie beyond the scope of this work. The important point, for present purposes, is how this research suggests that there are various biological units of age simultaneously at play within every organism, each with its own underlying processes. Cells constituting different organs may have radically different aging values. To make things worse, these differences become the more striking the lower we go in scale, so that we have a hierarchy of senescence: organismal, structural, cellular, chromosomal, and many more. Given how different and independent these mechanisms are, does it even make sense to talk about the age or aging of an organism *tout court*? Chronological age still corresponds to lifespan and, as such, it can be measured from birth to death. But what about the biological age of entire organisms? How can these notions be constructed?

One simple solution would be to determine the aging of an organism by calculating its overall aging value as the additive sum—or some other linear function—of the various kinds of aging processes at play. The idea is intuitive. For the sake of simplicity, suppose that in every organism there are ten aging processes simultaneously at play. Now, suppose that we could effectively measure and quantify these ten processes and assign to each and every one of them a numerical value. Now, the suggestion runs, we could determine the overall aging of the organism by treating it as the additive sum of these ten values or, alternatively, some other linear function. The outcome of this operation represents the overall biological-age value of an organism. We can then use this value to compare the process of aging across organisms and contrast classes. Great! But does this solve the problem?

A little reflection reveals that any numerical quantification along these lines would be sheer nonsense. Two problems are especially evident. First, there is no reason to expect the values in question to add up in a linear fashion. The following example should help drive the point home. Assuming, as we did above, that there are ten distinct biological aging processes at play in an organism, suppose that two conspecific individuals belonging to the same age group have exactly the same overall biological aging value. Does this give us any reason to conclude that they have aged in the same way? Clearly not. The reason is obvious. The assumption of linearity presupposes that each underlying process counts as much or as little as any other. Thus, if we consider two processes which add up to the same value, their contribution to the overall aging of the organism will be identical. This assumption is unwarranted. Don't panic. There's a simple fix to this hiccup: drop linearity. We need a *weighted* value for each component, a way to discern how much each specific subprocess contributes to overall biological aging.

Nevertheless, these considerations lead us to a second, more serious problem with the idea that biological aging can be operationalized as a function, a combination of several underlying constituent processes. To provide a meaningful weighted

value, we need to compare the specific contribution of each subprocess. Now, what is the common denominator that allows us to measure the specific input of the various types of aging? The obvious answer is chronological age, that is, physical time. The rationale is simple. Consider, once again, the concept of age mosaicism, the idea that different parts of an organism may vary quite drastically when it comes to chronological age. To wit, some cells in my body are a few days old, whereas others I may be carrying from birth. In order to measure differences in biological aging, we appeal to chronological age, that is time: 3-days-old versus 3-months-old versus 3 years-old versus 30-years-old. But, as just noted, there simply is no guarantee that a 35-year old neuron is 35 times older than a 1-year old cell.

In sum, the observation that there are various, distinct and independent processes of aging underlying any specific organism questions the possibility of developing a coherent, overall measure of the biological aging of an organism. I should make it very clear that I am not arguing against the notion of age mosaicism, which strikes me as quite plausible. My point is rather that the very idea of age mosaicism presupposes a notion of biological age that is characterized in terms of physical time—what I have dubbed ‘Einstein’s dictum.’ However, since biological age, as opposed to its chronological counterpart, is not a direct function of physical time, we have no way of providing a clear, operational, and quantifiable notion of biological age.

What should we conclude from these observations? The following section explores some options. Rather than throwing in the towel and embracing a radical form of aging pluralism, I suggest that the appropriate response is to eschew Einstein’s dictum and develop a biologically kosher notion of time.

4 Toward a biological conception of time

Section 3 focused on some conceptual difficulties in the operationalization of age, aging, and time. Historically, age and aging have been viewed as holistic properties of organisms. Intuitive as it may seem, does this assumption withhold serious scrutiny? Complications notwithstanding, we can talk about the *chronological* age of an entire organism: time elapsed since birth. But recent discoveries reveal an age mosaicism, according to which different parts of an organism are subject to different ages and aging processes. Consequently, finding a common denominator that allows us to talk about the overall *biological* age of an organism is hardly trivial. What follows from this? What moral should we draw from these reflections?

One possible reaction is to bite the bullet and reject the very idea that we can meaningfully talk about the overall biological age of a whole organism in any scientifically kosher sense. From this perspective, there simply is no quantifiable value that captures how much a complex system has aged during a specified stretch of time. Similarly, we have no overarching way of comparing its overall aging with the corresponding senescence across conspecific individuals. We must accept the dire conclusion that the biological age of an organism is no more than a metaphor, a figure of speech. Strictly speaking, complex individuals like us are a collection of miscellaneous, disconnected values. In sum, the suggestion runs, we should abandon the idea of providing an overarching assessment of the biological age of an

organism. We can only talk about my cellular age, my chromosomal age, my neural age and so forth. But these values do not combine in any significant fashion.

This radical form of ‘aging pluralism,’ strikes me as deeply unsatisfactory, as it ends up throwing the baby out with the bath water. To be sure, there are specific circumstances in which it is beneficial to focus on the specific senescence of an organ, system, or part of an organism. For instance, the study of degenerative diseases, such as Huntington or Alzheimer’s, focuses on the effects of the dysfunction in the brain, such as dementia (see Boniolo 2021). Or, to stick with a sadly current issue, understanding the aging of the respiratory system may prove important in the ongoing fight against COVID-19. Still, it deeply matters to gerontology how changes in, say, metabolic or other cytological systems contribute to our overall biological aging. This is how evolutionary biologists have historically framed the issue of aging (Garson 2021). And for good reason. As a patient, I am interested on how *I* am aging, as a whole, not merely in a piecemeal fashion. To put this in slightly different terms, what we need are biomarkers of functional aging that are applicable to an entire organism (Green and Hillersdal 2021). This being so, let’s explore an alternative approach.

Our task is to provide a coherent measure of the overall biological age of an organism, compatible with the observation that different parts of an individual may age at different rates, and the overall outcome cannot be a mere sum—linear or non-linear—of specific subprocesses. The hiccup is simple. Biological age is commonly understood as a function of chronological age, and chronological age is straightforwardly reducible to chronological time. But biological age cannot be expressed merely as a function of physical time. There is a failure of transitivity. How do we get out of this pickle?

Simplistic diagnoses call for simplistic solutions. We need to develop a notion of age that captures and encompasses not merely how long an organism has been alive (chronological age) but also how the individual in question has been affected by the passage of time (biological age). Chronological age presupposes chronological time. Biological age requires biological time. Hence, what we need is a notion of biological time to provide a common measure to compare and add up the various subprocesses and generate an overall notion of biological that applies to organisms as a whole.

What could this ‘biological time’ look like? We need not come up with a suggestion from scratch, as there are various extant theories that already fit the bill. Sholl (2021) provides an overview of frameworks that purport to unify the scattered knowledge concerning aging. Allow me to borrow some of his insights to establish the main idea underlying my proposal.

One influential strategy, which has recently gained some traction in the literature in aging, involves characterizing aging in terms of *entropy*. Entropy, as every beginning student of physics knows quite well, is a thermodynamic quantity representing the availability of a system’s thermal energy for conversion into mechanical work. From this perspective, entropy becomes a useful proxy that can be used to measure and quantify the degree of order and disorder present within a system. The lower the entropy, the more organized the system. The higher the entropy, the more chaotic, disorganized the system becomes. Left to their own device, physical systems

spontaneously shift from a more-ordered, lower-entropy state, to a less-ordered, highly-entropic state, according to the second principle of thermodynamics.

How is any of this connected to aging? The basic intuition is simple. If we take the death of an organism to coincide with its state of maximum disorder—that is, its highest entropic value—and, conversely, we identify birth with the lowest entropic state, then we can keep track of both the passing of time (chronological age) and explain its effects on the organism (biological age) in terms of the increasing entropy within the system itself (Hershey 2010). Incidentally, as two anonymous reviewers have brought to my attention, the entropy of an organism will continue to decrease after death, at the decomposition stage. Hence, strictly speaking, death is the highest entropic state of a *living* organism. Whether or not organisms cease to be so post-mortem is an interesting issue, albeit one that I shall sidestep.

Let's explore this further. In an influential 1951 lecture, Sir Peter Medawar (1981a), an eminent evolutionist and one of the pioneers of an evolutionary approach to aging (Garson 2021), dubbed our failure to comprehend how and why biological aging occurs “an unresolved problem in biology.” Almost seventy years after this pronouncement, various scholars have boldly proclaimed that Medawar's problem has finally been ‘solved’ (Holliday 2006; Hayflick 2007a, b). The general proposal is that aging is a stochastic process that ought to be understood in terms of entropy (Yates 1988). Specifically, this is how Hayflick (2007a, pp. 3–4) puts it:

The common denominator that underlies all modern theories of aging is change in molecular structure and, hence, function. This phenomenon can also be called increasing loss of molecular fidelity or increasing molecular disorder. It can be viewed as an increase in entropy which adheres to the more recent interpretations of the Second Law of Thermodynamics that do not include the necessity for a closed system. (...) Aging is an increase in molecular disorder. It is a stochastic process that occurs systematically after reproductive maturity in animals that reach a fixed size in adulthood. This escalating loss of molecular fidelity ultimately exceeds repair and turnover capacity and increases vulnerability to pathology or age-associated diseases.

Of course, dropping the requirement of a closed system raises the importance of environmental influences in fully understanding the entropy of systems.

This approach, it is subsequently claimed, accounts for four phenomena that characterize the finitude of life: aging, the determinants of longevity, age-associated diseases, and death. An interesting implication of this perspective is that aging and, eventually, death, are inevitable consequences of life, regardless of progress in the medical field. As Hayflick (2007a, p. 11) provocatively puts it, “Even if biomedical research is completely successful in eliminating all causes of death currently written on death certificates, human life expectancy could only be extended by about 15 years.”

In short, characterizing age in terms of increases in entropy is a contemporary influential strategy, which does not require aging to be understood in terms of physical time. This, clearly, is independent of entropy per se. indeed, similar conclusions can be reached through different avenues.

Consider a different approach to aging, centered on the notion of *homeodynamic space* (Rattan 2007, 2019). The concept of homeodynamic space, succinctly put, captures the evolved capacity of organisms to adapt to a shifting environment. Homeodynamic space, in other words, purports to reflect the survival ability, or buffering capacity of biological systems, which corresponds to an organism's intrinsic power to maintain a healthy state. From this perspective, the process of aging can be understood as the progressive loss of these capacities. Aging, to put it slightly differently, becomes the progressive shrinking of homeodynamic space (Holliday 2006; Yates 2007). I should stress that none of these tenets is uncontroversial—for instance, a scorching critique of homeodynamics has been articulated by Uffink (2007b).

Another recent general approach to aging is built upon the concept of the *pathosome*. The basic idea underlying the pathosome is that an individual's phenotype can be seen as a proxy for the history of the interactions between their genotype and environment (Lenart et al. 2019). As Sholl (2021) nicely puts it, “with knowledge of phenotype and age, an individual's current phenotype can be used to estimate the past effects of the environment on that individual, resulting in the mapping of a unique ‘phenotypic trajectory’.”

The details of all these proposals need not concern us here. The important observation, for present purposes, is that all these theories point to the same conclusion. Age has a temporal dimension, but this temporality need not correspond—and indeed, will generally not correspond—to a single, overarching physical notion of time, that is, chronological age. Biological age can be identified and explained as a gradual increase in entropy, in terms of evolved design, as the development of pathosomes or ageotypes, changes in circadian clocks (Welz and Benitah 2019), the scaling of metabolic rates, or as something altogether different. Sure, all these units of age can be *measured* in terms of physical time. But units of age need not be reducible to any specific physical units, in the sense that in the same physical interval, two biological organisms, or even parts of the same organism, can age in very different ways. And, yet, this makes these units of age no less real, objective, or scientifically significant. In short, Einstein's dictum poses unnecessary strictures on our understanding of aging. Time need not only have an objective physical dimension and a subjective psychological one. Different cellular populations are governed by their specific process, each governed by its own molecular clock, and each with its own arrow of time and its own velocity. This is what underlies the truism that entities and organisms may age differently, despite having the same age. Beneath all of these proposals lies, more or less explicitly, a *biological* notion of time.

In conclusion, several notions of time may or may not correspond across organisms, organs, and cells, while remaining perfectly objective. From this standpoint, it is useful to conceive of time not as physical quantity, but as a collection of arrows, along the path blazed by Boltzmann (Reichenbach 1956). Age mosaicism shows that age is best depicted as a mosaic of time arrows, where each ‘tile’ evolves at its own pace. Only thus can we make sense of organisms aging as a whole. Biological age must be characterized against the backdrop of a biological notion of time, not a physical one.

5 Concluding remarks

Time to take stock. This essay began with the idea that physics provides a unique, objective conception of time. I dubbed this tenet ‘Einstein’s dictum’ because of the great physicist’s explicit rejection, in the course of his heated debate with Bergson, of any alternative conception of time which could rival the objectivity of physical time. Time can either be understood physically or psychologically. *Tertium non datur*. Einstein’s dictum, I maintained, has become widely entrenched within scientific practice. This is evidenced by how the relation between age, aging, and time is standardly conceived. Chronological age is typically assumed to be straightforwardly reducible to an underlying notion of physical time. Biological age, in turn, is understood by reference to chronological age—that is, physical time—which makes it objective and provides a common measure for operationalization, the quantification of biological age within the life sciences. I argued that this exclusive identification of time with physical time may be a mistake. The relation between chronological and biological age is much subtler and more complex than it is often assumed. The reason, succinctly put, is that cutting-edge research shows that organisms do not age as a cohesive whole. *Au contraire*, the life expectancy of individual cells ranges from a few days to entire lifespans, triggering a phenomenon that has been dubbed ‘age mosaicism.’ These considerations point to the importance and, indeed, the necessity of cashing out an underlying notion of biological time, which provides a common measure for assessing, comparing and, ultimately, quantifying both the chronological and the biological age of an organism. Cut the pie any way you like, identifying time with physical time ain’t gonna do the trick. What is needed is a distinctive notion of *biological time*. That is, we need a specific notion of time, understood biologically, not directly reducible to physical terms. These exquisitely biological aspects of age and time are already recognized, more or less explicitly, in contemporary aging studies. We need to take the final step and drop Einstein’s dictum.

So, what exactly follows? What overarching morals should we draw from this discussion? I tried to make it very clear that it would be a mistake to infer that Einstein was wrong about the nature of time. As Bergson saw quite clearly, Einstein’s chief aim was to provide an operationalization of a specific, physical notion of time, in the context of his theory of relativity. That he brilliantly accomplished. Nevertheless, he may have been too rash in dismissing the idea that time can have different, non-physical dimensions that are no less objective than a physical one. Different fields and subfields of science may require different ways of measuring time, all of which are perfectly objective. Aging, in particular, requires its own temporal backdrop. This may or may not coincide with Bergson’s ‘philosophical’ conception—which, as mentioned at the outset, is complex and slightly esoteric. Of course, modern gerontologists seldom, if ever, explicitly refer to Einstein’s quarrel with Bergson, and the impact of physics on aging studies is, at best, an indirect one (Uffink 2007a). Yet, an oblique influence of the Einstein-Bergson debate on modern characterizations of time is hard to overstate.

It turns out that Einstein's dictum, the tenet that the true nature of objective time belongs exclusively to the domain of physics, is unduly restrictive.

Allow me to conclude with a nod to another important, if unconventional and less scholarly influence. The title of this essay, and much insights herein, are inspired by the lyrics of an oldie-but-goodie song by the seminal band *Chicago*. 'Does anybody really know what time it is? Does anybody really care?' When it comes to the study of aging, both questions can, and should, be answered in the negative. And it might just be for the better.

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References

- Arrojo e Drigo, R., Lev-Ram, V., Tyagi, S., Lechene, C., Ellisman, M. H., & Hetzer, M. W. (2019). Age mosaicism across multiple scales in adult tissues. *Cell Metabolism*, *30*, 343–51.
- Baars, J. (2007a). A triple temporality of aging: Chronological measurement, personal experience, and narrative articulation. In H. Visser & J. Baars (Eds.), *Aging and time: Multidisciplinary perspectives* (pp. 15–42). New York: Baywood.
- Baars, J. (2007b). Introduction: Chronological time and chronological age—Problems of temporal diversity. In H. Visser & J. Baars (Eds.), *Aging and time: Multidisciplinary perspectives* (pp. 1–14). New York: Baywood.
- Boniolo, G. (2021). Demented patients and the quandaries of identity: Setting the problem, advancing a proposal. *History and Philosophy of the Life Sciences*, *43*(1), 1–16.
- Bridgman, P. W. ([1958] 1927). *The logic of modern physics* (8th ed.). New York: Macmillan.
- Canales, J. (2015). *The physicist and the philosopher: Einstein, Bergson, and the debate that changed our understanding of time*. Princeton and Oxford: Princeton University Press.
- Garson, J. (2021). Ageing and the goal of evolution. *History and Philosophy of the Life Sciences*.
- Green, S. M., & Hillersdal, L. (2021). Aging biomarkers and the measurement of health and risk. *History and Philosophy of the Life Sciences*.
- Hayflick, L. (2007a). Biological aging is no longer an unresolved problem. *Annals of the New York Academy of Sciences*, *1100*, 1–13.
- Hayflick, L. (2007b). Entropy explains aging, genetic determinism explains longevity, and undefined terminology explains misunderstanding both. *PLoS Genetics*, *3*(12), 2351–54.
- Hershey, D. (2010). *Entropy theory of aging systems: Humans, corporations, and the universe*. London: Imperial College Press.
- Holliday, R. (2006). Aging is no longer an unsolved problem in biology. *Annals of the New York Academy of Sciences*, *1067*, 1–9.
- Lenart, P., Scheringer, M., & Bienertova-Vasku, J. (2019). The pathosome: A dynamic three-dimensional view of disease–environment interaction. *BioEssays*, *1900014*, 1–6.
- Maung, H. H. (2021). What's my age again? Age categories as interactive kinds. *History and Philosophy of the Life Sciences*.
- Medawar, P. B. ([1952] 1981a). An unsolved problem in biology. In *The uniqueness of the individual*. New York: Dover.
- Medawar, P. B. ([1952] 1981b). *The uniqueness of the individual*. New York: Dover.
- Rattan, S. (2007). Homeostasis, homeodynamics, and aging. In J. Birren (Ed.), *Encyclopedia of gerontology* (pp. 696–699). Amsterdam: Elsevier.
- Rattan, S. (2019). *Age*. Aarhus: Aarhus University Press.
- Reichenbach, H. (1956). *The direction of time*. Berkeley and Los Angeles: University of California Press.

- Sholl, J. (2021). Can aging research generate a theory of health?' *History and Philosophy of the Life Sciences*.
- Uffink, J. (2007a). Time and aging: A physicist's look at gerontology. In H. Visser & J. Baars (Eds.), *Aging and time: Multidisciplinary perspectives* (pp. 137–60). New York: Baywood.
- Uffink, J. (2007b). Whence the emergence of biological time? In H. Visser & J. Baars (Eds.), *Aging and time: Multidisciplinary perspectives* (pp. 169–76). New York: Baywood.
- van der Meer, E. (2007). Psychological time: Empirical evidence, theories, and aging-related effects. In H. Visser & J. Baars (Eds.), *Aging and time: Multidisciplinary perspectives* (pp. 44–82). New York: Baywood.
- Welz, P.-S., & Benitah, S. A. (2019). Molecular connections between circadian clocks and aging. *Journal of Molecular Biology*, 43(12), 3661–3679.
- Yates, F. E. (1988). The dynamics of aging and time: How physical action implies social action. In J. Birren & V. L. Bengston (Eds.), *Emergent theories of aging* (pp. 90–117). New York: Springer.
- Yates, F. E. (2007). Biological time as an emergent property. In H. Visser & J. Baars (Eds.), *Aging and time: Multidisciplinary perspectives* (pp. 161–68). New York: Baywood.

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