European Journal for Philosophy of Science (2024) 14:23
https://doi.org/10.1007/s13194-024-00583-8

PAPER IN THE PHILOSOPHY OF THE SOCIAL SCIENCES AND HUMANITIES

Overdetermination, underdetermination, and epistemic granularity in the historical sciences

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Received: 30 September 2022 / Accepted: 26 April 2024 / Published online: 30 May 2024

Abstract

The optimism vs. pessimism debate about the historical sciences is often framed in terms of arguments about the relative importance of overdetermination vs. underdetermination of historical claims by available evidence. While the interplay between natural processes that create multiple traces of past events (thereby conducive of overdetermination) and processes that erase past information (whence underdetermination) cannot be ignored, I locate the root of the debate in the epistemic granularity, or intuitively the level of detail, that pervades any historical claim justification network. To reveal the role played by granularity, I elaborate a model of historical claim justification. This model maps out the different elements that enter the justification of historical claims (incl., actual and inferred states of affairs, dating and information reconstructing theories). It also incorporates the different types of processes that affect traces of past events (information creating, preserving, modifying, and destroying processes). Granularity is shown to play a pivotal role in all elements of this model, and thereby in the inferred justification of any historical claim. As a result, while upward or downward shifts in granularity may explain changes about claims being considered as overdetermined or underdetermined, epistemic granularity constitutes an integral part of evidential reasoning in the historical sciences (and possibly elsewhere).

Keywords Epistemic granularity · Information granulation · Coarseness · Overdetermination · Underdetermination · Historical sciences

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1 Introduction

The very possibility of knowing anything about the past requires that evidence about this past be accessible. Yet, evidence often gets erased with time. Should we therefore be optimistic or pessimistic about the feasibility of elaborating knowledge about the past? In the eyes of optimists, past events leave numerous traces, in any case enough to make robust inferences about what happened: they are "overdetermined" by the traces they have left (Cleland, 2002). Pessimists on the other hand stress that much of the past will remain forever inaccessible due to the ineluctable destruction of evidence with time. Hence the possibility of coexisting rival claims about the past that are said to be "locally (or weakly) underdetermined" by evidence in the sense of us not being able to choose between any of them on the basis of current knowledge and available evidence (Kleinhans et al., 2005; Turner, 2005).[1]

Yet, contrary to the optimistic view, the identification of convincing traces or "smoking guns", as proponents of overdetermination would have it, is rarely if ever the rule. Instead, some have proposed that it is the convergence or "consilience" of several factors, all pointing in the same direction that, in the end, provides claim justification (Forber & Griffith, 2011). On the other hand, contrary to the pessimistic view, prototypical cases of local underdetermination, such as the famous case of the color of dinosaurs, have been refuted just a few years after being formulated (Turner, 2016). Overdetermination and local underdetermination thereby offer at best incomplete framings of historical inquiry.

One obvious reason is that new evidence can always be discovered or made sense of, notably when novel instruments and theories become available, or when novel inferences are made that contribute to the evidential network (Wylie, 2002, chap. 11; Jeffares, 2008; Tamborini, 2020). Another reason, I argue here, is that historical claims are subject to reformulation at varying levels of granularity. Here, granularity refers to the degree of detail in the chosen description of a particular item of interest, often juxtaposed with alternative levels of detail, such as coarser or finer-grained descriptions (more about this in Section 6).[2]

[1] Turner opposes this "local underdetermination" that concerns a *given set* of competing hypotheses to a more general thesis of "global underdetermination" according to which, given *any* hypothesis, there would exist at least one strongly empirically equivalent rival. For more details see (Turner, 2005, 218); see also (Turner, 2007, 2009b). Similarly, Kleinhans et al. (2005) distinguish between "weak" and "strong" underdetermination.

[2] It is argued here that granularity plays a significant role in the justification networks that ground historical claims, but granularity is relevant to numerous other debates. Granularity matters when it comes to characterizing the uniqueness of events (Tucker, 1998), such as the evolutionary appearance and transmission of specific traits (Wilkins & Godfrey-Smith, 2009; Buskell & Currie, 2021; Bourrat & Charbonneau, 2022) or the very origin of life (Malaterre, 2024). Formally, granularity is also present in the metaphysics of causation literature, especially when it comes to individuating events as causal relata (Dretske, 1977; Hitchcock, 2012), in explanation accounts (Strawson, 1985; Jackson & Pettit, 1992) as well as in the philosophy of language literature, for instance when it comes to the question of individuating propositions (King, 2013; Collins, 2014). Maybe more significantly, granularity has been much studied in the context of fuzzy logic, providing a cornerstone for the emergence of so-called "granular computing" (Zadeh, 1997; Yao, 2008). There should be value in connecting these different lines of reasoning, notably through formal explications of the different usages of granularity, but this endeavor is beyond the scope of the present paper.

This may be considered as relatively trivial but is often overlooked. Indeed, a striking feature of both the overdetermination and the underdetermination views is their framing of historical claims as claims implicitly formulated at a specific fixed granularity. The debate about the local underdetermination of the color of dinosaurs considered that all fine-grained information relevant to pigmentation had been lost, hence the formulation of a coarse-grained claim according to which "the color of dinosaurs" was underdetermined. However, as often happens during historical investigation, claims can be—and often are—reformulated at different granularities, which may then affect their status as being either over- or underdetermined. The playing field of the historical sciences is a dynamic one in which impossibility claims justified by local underdetermination are often overcome, while claims justified by overdetermination are subsequently replaced by open questions and underdetermined hypotheses (Tucker, 2011).

The issue is compounded by the fact that historical claims often consist of sets of interconnected statements whose over- or underdetermined status may vary, as well as that of their interconnections—even in the apparently simple case of the color of dinosaurs, as we will see. In many instances, historical claims even connect numerous individual statements into intricate narratives.[3]

By elaborating a model of historical claim justification, the objective here is to unpack the set of inferences by which historical claims become justified, and by so doing to reveal the role played by granularity in claim justification and thereby in the overdetermination vs. underdetermination debate. Three examples run through the argument: the well-discussed case of the color of dinosaurs; the K-Pg mass-extinction; and the common-sense toy example of the broken window.[4]

The chain of reasoning is as follows. First, after reviewing the overdetermination (OD) and local underdetermination (LU) theses, I map out four types of natural processes that affect the current presence of information about the past: information creating, preserving, modifying, and destroying processes (Section 2). A further examination of cases of OD and LU claims (and of their refutation) reveals the role played by the implicitly assumed granularity of the claims and of their inferential basis (Section 3). To provide an overarching view of the elements that compose historical inferential networks, a model of historical claim justification is then proposed (Section 4). This model makes it possible to understand how epistemic granularity finds its way into the evidential reasoning that grounds historical claims (Section 5). OD and LU theses are then analyzed in light of this model and of the presence of epistemic granularity (Section 6). Finally, the broader role of this granularity in historical debates and their unfolding is discussed (Section 7).

[3] On narratives, see for instance: (Goudge, 1967; White, 1973; Hull, 1981; Ankersmit, 1983; O'Hara, 1992; Kuukkanen, 2015; Currie & Sterelny, 2017).

[4] The K-Pg mass extinction was formerly known as the Cretaceous-Tertiary (K-T) extinction (Alvarez et al., 1980). The Tertiary period has since been divided into two periods: the Paleogene and the Neogene. Hence the new name of the Cretaceous-Paleogene (K-Pg) extinction.

2 OD, LU, and information-affecting processes

The main idea behind overdetermination (OD) is that past states of affairs usually leave many more traces in the present than are required to infer these past states on the basis of present states of affairs. In this sense, past states of affairs tend to be overdetermined by present states of affairs (Lewis, 1979). Take the classic example of the window that has been shattered by a baseball: the shattering leaves out many more glass fragments than required to infer that the glass has been broken (Cleland, 2002). This is the case even after cleaning has taken place, for there is always the possibility that a tiny fragment just slid under the fridge or found its way in a floor crack. Dinosaurs too leave many traces, not just fossilized body parts but also fossilized traces of their activities (ichnofossils) including footprints, feeding marks or even droppings (coprolites). And so do meteoritic impacts which not only form craters but also create deposits of iridium and various other metals as well as rocky spherules, shocked quartz and microscopic diamonds resulting from the energy of the impact itself. For Cleland, the historical sciences precisely exploit overdetermination to elaborate and justify claims about the past. Historians typically observe traces, hypothesize common causes for these traces and use discriminating evidence—"smoking guns"—to choose among competing hypotheses (Cleland, 2002). What makes this method effective is that the world is such that causes usually produce numerous effects. This is to say that, through varied processes—that I will call here "information creating processes" (ICPs)—past states of affairs usually leave many more traces, smoking guns included, than needed to infer their existence. As a result, historical claims about past states of affairs usually turn out to be epistemically overdetermined by observations of present states of affairs, hence an optimistic perspective on the possibility of justifying historical claims.

Yet, the extent to which OD actually obtains among historical claims is open to debate. Though past states of affairs do usually tend to leave many traces, there are also numerous information destroying processes (IDPs) that tend to erase these traces (Sober, 1988). In practice, under-the-fridge shards of glass are cleaned up when fridges are moved and replaced. Body parts, footprints and droppings are taken apart by other organisms or simply weathered out. Meteoric impacts get eroded, and their dust is transformed through diverse metamorphic processes. Consequently, IDPs justify a more pessimistic view on historical claims: a view according to which there exist sets of claims about past states of affairs that will always remain undetermined by present states of affairs. This idea is what motivates the thesis of the "local underdetermination" (LU) of historical claims by present evidence (Kleinhans et al., 2005; Turner, 2005): local underdetermination occurs when competing claims happen to be equally well supported by present evidence while available background information suggests that the tie will likely never be broken.[5]

In between the two extremes of ICPs and IDPs, a broad range of other processes exist that neither properly create nor destroy information, but simply preserve or

[5] Of course, this is not to say that all historical claims raise OD or LU questions: some historical claims (and likely most) simply appear appropriately justified by evidence, at least given a specific knowledge context.

modify information to different degrees. These processes explain why traces remain at all and why they can be used to make reliable inferences about the past. Let us call "information preserving processes" (or IPPs) those processes that contribute to preserving past traces nearly in their intact forms. They can be viewed as acting against IDPs. A hot sun can bake mud footprints while a flashflood covers them with sediments making possible their fossilization, hence their preservation over millions of years. More generally, many processes can increase the durability over time of specific features of interest. As is known to Egyptologists, embalming preserves human remains; dryness preserves wooden artifacts; and darkness preserves pigments and colors.

On the other hand, "information modifying processes" (IMPs) can be thought of as processes that alter information about past states of affairs, sometimes very significantly but in such ways that the resulting presently accessible traces can be used to infer, with the help of specific background theories, the original information. For instance, in archaeology, it is known that larger artifacts tend to move upward in the archaeological record compared to smaller ones (the so-called "size-effect"), hence important consequences on the distribution of exposed artifacts. Numerous other physical processes modify information about past features in known ways: structures get distorted by gravity and pressure; molecular compounds are transformed through heating and pressure in specific ways; ratios of unstable isotopes change through time according to their known half-life (hence for instance the possibility of radiocarbon dating to determine the age of carbonaceous materials).

Whereas IPPs make it possible to infer information about past states of affairs directly from present states of affairs with little or no background theory, IMPs typically require the use of additional—and often quite sophisticated—background theories. Background theories may be mobilized as well when accounting for ICPs and IDPs, but similarly to IPPs, this is not their distinguishing feature. In this taxonomy, the four types of processes can be thought as occupying different positions in a continuum, depending on how they affect information: ICPs have a positive effect onto information, typically multiplying it; IPPs can be viewed as neutral, simply preserving information over time; IMPs modify information but only to a limited extent, and in ways that are understood; as for IDPs, they alter information up to the point that what remains—if anything—cannot be made sense of. While ICPs conjoined with IPPs and IMPs lend support to the overdetermination of (at least some) hypotheses about the past by presently available evidence, IDPs provide the main motivation for endorsing local underdetermination about (at least some) other historical claims.

3 Problems with OD and LU

Needless to say, all four types of information-affecting processes (ICPs, IDPs, IPPs and IMPs) take place concurrently. Depending on their relative influence, information about some specific past states of affairs will be more easily obtained compared to information about other past states of affairs. As a result, two consequences can be drawn. First, it is far from obvious which (if any) of the optimistic or pessimistic views should prevail in the historical sciences: the extent to which OD cases may exceed LU cases hinges on

the relative predominance of the four information-affecting processes in the real world. Though this is an empirical question, the sheer number of conceptually possible hypotheses one may formulate about past states of affairs makes it intractable.[6]

Second, the issue is compounded by the fact that our access to presently available information as well as our ability to infer from it information about past states of affairs may strongly vary from case to case. Access to information indeed depends on multiple contingent factors, from practical considerations (choice of investigation site; geo-climatic accessibility restraints; financial and technological limitations) to epistemic constraints (current state of knowledge, hence of available instruments with which to "read" present information). As for our ability to make sense of the collected information in terms of information about past states of affairs, it is eminently contingent on available background theories. Not only do these factors differently affect different historical questions, but their significance for a given question may also change over time. In particular, novel pieces of information can be uncovered (for instance in newly discovered sites or with the assistance of novel technology), while old ones can receive new readings (for instance from novel instruments) or be interpreted in new ways (with new background theories).

This explains why some cases of LU do not hold. Take the example of the color of dinosaurs which was considered as a clear example of LU in 2005 (Turner, 2005): at that time, our background theories about taphonomy (our knowledge about how organisms decay and become fossilized or preserved) gave us good reasons to believe that all past information about the color of dinosaurs had for ever been destroyed. As a result, it was reasonable to claim that no one would ever know which colors the dinosaurs were, hence a clear case of LU. Yet, some years later, advances in our understanding of how biological pigments were packed in different types of organelles (melanosomes), which might then fossilize into different shapes and patterns, made it possible to infer the coloring of the feathers of the small therapod dinosaur *Sinosauropteryx* (Zhang et al., 2010). The color of dinosaurs could no longer be said to be a case of LU (Turner, 2016). Quite the contrary, it appeared as an additional illustration of OD: *Sinosauropteryx* had millions of pigment-packed organelles (hence ICPs), many of which got destroyed (through different types of IDPs) while some were preserved or partly modified (via IPPs and IMPs); and today, just a few of them are sufficient for inferring color patterns (hence OD).

Yet, as soon as one question is answered, as Turner incidentally notes, other questions crop up: What can we say about the color of other dinosaurs? If we know the color of an adult *Sinosauropteryx*, what can we say about the color of a juvenile *Sinosauropteryx*? And among these questions always lurks the possibility that indeed one will give rise to LU. Forber and Griffith (2011) make a similar point when disputing Cleland's (2002) view on the historical method and the role of smoking guns in the historical sciences, notably in the case of explaining the Cretaceous-Paleogene (K-Pg) boundary mass extinction. While arguing that, in fact, several lines of evidence contributed to justifying the meteoritic hypothesis (not just smoking guns), they also recognize in passing that novel and finer-grained questions may appear, for instance

[6] This argument can be used to defend agnostic positions (Forber, 2009; Havstad, 2019).

whether presently available fossil distributions can be used to discriminate between gradual and simultaneous extinction hypotheses. So, even in the case where multiple lines of evidence are available (thanks to different types of information-affecting processes) and can be reconciled to support one particular historical claim (hence a case of OD), novel questions can still be formulated that bring back the ghost of LU.

A common reason for the apparent failure of both the OD and LU views is their lack of recognition of the role of granularity in the formulation and justification of historical hypotheses. Both views typically consider that the objective of a historical investigation is to identify the "whodunit" (Turner, 2009a), with this "whodunit" belonging to an implicitly agreed upon class of factors. Yet, as the examples above have shown, the classes of factors can vary depending on the framing of the research question: the whodunit can be a dinosaur, a dinosaur with feathers, a *Sinosauropteryx*, a juvenile *Sinosauropteryx*, the tail feathers of a juvenile *Sinosauropteryx*, the patterns on the tail feathers of a juvenile *Sinosauropteryx* and so forth. Even in the toy example of the broken window, the type of whodunit can significantly vary depending on context. The ball could be a baseball, a tennis ball, a squash ball, a spike ball. A baseball could be specified (or not) as a "safety ball", a "reduced injury factor baseball", a "youth tournament baseball", a "practice baseball", a "professional-grade baseball", each with different mechanical and aerodynamic characteristics.[7] What's more, a professional-grade baseball could be brand new, or worn out; with specific markings, signed, scratched, with a phone number, fingerprints, or DNA fragments.

Changing granularity in formulating a historical claim is not idle: it affects the justification basis for the claim and whether OD or LU should prevail. If the only presently available trace of the window-shattering baseball is a photo picture of the window frame (say, the actual ball has been thrown away, and no one checked for fingerprints), then LU will be highlighted to justify the impossibility to ever prove whether the ball was hit by Sue or Denis based on their fingerprints (assuming there is no other way to distinguish between Sue and Denis here). In that case, the claim "the window was shattered by a baseball" remains justified, while the claim "the window was shattered by a baseball thrown by Sue" is subject to LU. Conversely, if the ball is available and fingerprints are found on it, then OD will be highlighted to justify why it was possible to pin down Sue. In that case, the claim "the window was shattered by a baseball thrown by Sue" will be justified. Still, if there is no interest in finding who of Sue and Denis did it, then it is plausible that neither OD nor LU would be mentioned.

4 From traces to historical claims: A model of historical claim justification

For any historical claim to be at all justified, some present trace must be available from which information about a past state-of-affairs can be inferred. Indeed, if all glass shards have been carefully cleaned up and if the window has been replaced

[7] I owe this encyclopedic knowledge about baseballs to https://99baseballs.com/equipment/baseballs/different-types-of-baseballs-for-different-ages/ (accessed May 6th, 2021).

(imagine that I acquire the house long after the event), there would be no reasons to believe that the window was ever broken, and even less that this was caused by the impact of a baseball thrown by Sue. So at least some trace must be available for any historical claim to receive even the slightest amount of justification. In other words, historical justification starts with some specific information being extracted from a present state-of-affairs (SA_p): shards of glass, an anomalous iridium enrichment, fossilized melanosomes (Fig. 1). Working backward from this presently available information, one formulates factual statements—such as "A baseball shattered the window", "A giant meteorite impacted the Earth", or "*Sinosauropteryx* had a tail with dark-colored stripes"—that constitute an inferred or reconstructed past state-of-affairs (SA_t^*) which in turn is justifiably taken to summarize the relevant features of an actual past state-of-affairs (SA_t) given a question of interest.[8]

The justification of such individual factual statements hinges on their evidential support (presently available information) as well as on specific background theories (and relevant instruments) of at least two sorts: theories that help position statements sometimes in the past, and theories that make it possible to infer how things were in that past compared to how they are now.[9]

Indeed, saying something about the past implies being able to somehow date that thing, hence the use of chronological dating theories (CDTs): theories that make it possible to position the inferences some specific time back in the past (Wylie, 2020). Relative dating theories are one type of chronological dating theories used in the historical sciences. In paleontology, biostratigraphic correlations, for instance, make it possible to assess relative ages of rock strata by using the fossil assemblages they contain. In geology, the law of included fragments states that clasts in a rock are older than the rock itself, while the law of superposition asserts that strata that lie at the bottom of an undeformed stratigraphic sequence are older than strata that are higher up, since the latter are formed by newer material that has deposited on top of older one over time. Absolute dating theories are another type of dating theories. Examples include radiometric dating methods such as radiocarbon dating (based on the decay rate of ^{14}C carbon isotope) or argon-argon dating (based on the decay rate of argon isotopes $^{40}Ar/^{39}Ar$), but also non-radiometric dating methods such as amino acid dating, which is based on changes in amino acid molecules depending on how

[8] When using the term "reconstructed", I simply mean that information is inferred and combined in order to get a best possible description of what happened. Since past states-of-affairs cannot be directly observed, any description must somehow be put together or constructed. I take these reconstructed states-of-affairs as consisting of (sets of) statements. Whether such reconstruction qualifies as one type or another of historiographic "constructivism" is another matter on which I remain agnostic (but see for instance Kuukkanen, 2015, 37–44). In any case, these states-of-affairs do not encompass all that happened at the time (e.g., birds stopped singing when the window got broken), but only those elements that are relevant for answering a particular question of interest (e.g., how did the window get broken?).

[9] Such background theories are sometimes referred to as "middle-range theories" (Kosso, 1993; Jeffares, 2008; Chapman & Wylie, 2016, chap. 1; Currie, 2018, chap. 5; Cartwright, 2020). There is however controversy about proper usage of the concept across different disciplines, from the social sciences where it originated to archaeology where it appears to be used in a variety of contexts, leading to possible confusion (Raab & Goodyear, 1984). For the purpose of the present argument, I do not enter this debate and prefer to use the more neutral notion of "background theories". I limit myself here to discussing two major types of such theories: "chronological dating theories" and "information reconstructing theories".

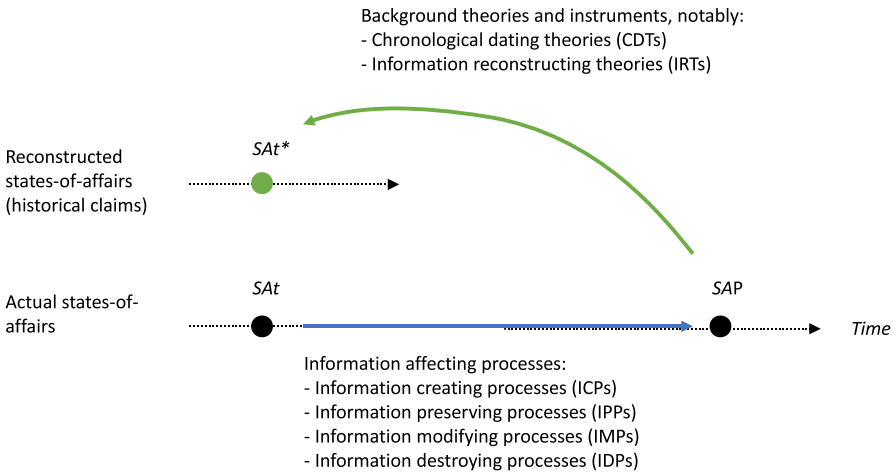

Fig. 1 Model of historical claim justification (reconstructed states of affairs are identified with an asterisk *; this is to make explicit that they consist of historical claims that rely on a number of justificative inferences)

long ago they were formed. Other examples include dendrochronology for tree-ring dating as well as obsidian hydration dating (OHD) for dating obsidian rocks on the basis of their water absorption rate, among many other such methods. Chronological dating of *Sinosauropteryx* as being 126 million years old used a combination of relative and absolute dating techniques (Zhou et al., 2003), and so did the dating of the K-Pg boundary at some 66 million years ago (Alvarez et al., 1980). Even in the toy example case of the broken window, I have a recollection of a series of past states-of-affairs according to which my window was intact when I left home this morning, a neighbor called at noon to tell me my window was broken, and I found out by myself that the window was indeed broken when coming home in the evening. The knowledge I have about, say, the reliability of my memory and the trustworthiness of my neighbor, lead me to position the shattering of my window sometimes between my departure from home and noon time, through an intuitive process that mixes common-sense relative and absolute dating approaches.

The second type of background theories that are needed are theories that help make sense of information available in present states-of-affairs in terms of information about past states-of-affairs. These theories typically capture the workings of IMPs (and to a lesser extent IPPs) that naturally occur: they justify how past states-of-affairs can be inferred or reconstructed (call them "Information Reconstructing Theories" or IRTs). Taphonomic theories are paradigmatic in this respect: knowing how specific cellular organelles fossilize, one can infer which types of melanosomes *Sinosauropteryx* had, thereby which pigments and colors it displayed. Theories from physics broadly speaking can be used to infer that the current iridium anomaly at the

K-Pg boundary was present in the exact same form some 66 million years ago. In other cases, other similar theories will be used to find out how things changed and how they were back in the past. Even in the toy example of broken window, I will use some of the implicit common-sense theories I hold about the world to reconstruct a past state-of-affairs in which the glass shards were scattered in the same pattern as I found them when coming home in the evening.

Very often, historical claims go beyond the formulation of individual factual statements: they assemble statements into larger explanatory units. This is made possible by the inference of connections between reconstructed past states of affairs, most notably causal connections that receive their justification from additional background theories and possibly other factual statements.[10] For instance, the presently available iridium anomaly at the K-Pg boundary of the rock record makes it possible not only to infer the presence of that anomaly 66 million years ago but also, and even more significantly, to infer the impact of a 10–15 km large asteroid at that time.[11] This second inference is made possible by the planetary sciences which have established that meteorites and asteroids contain a much higher abundance of iridium than the Earth's crust. Yet other inferences about past events were also made, notably a causal connection between the asteroid impact and the mass extinction of a wide range of species already noted in the paleontological record: here the causal link is the production by the impact of sufficient amounts of dust and particles in the atmosphere to block the sunlight, effectively shut off photosynthesis and thus stop the food chains at their very basis. This second inference is made possible by different theories linking the abundance of iridium found in the geological record to sizes of impactors, as well as Newtonian mechanics to infer the energy released by the impact, theories from the Earth sciences to infer the consequences of that impact in terms of climatic effects and biological theories about photosynthesis and ecosystem functioning (Pope et al., 1997). Implicit in these inferences is a generalized principle of uniformitarianism according to which presently valid theories from a diversity of disciplines were equally valid in the past (Page, 2021).[12]

Reflecting on the different elements mentioned so far, a more systemic model of historical claim justification can be elaborated. The model is illustrated on Fig. 2a with the toy example of the broken window. Different events or states-of-affairs in the past have been causally connected, say, for simplicity, a state-of-affairs SA_1 (a baseball impacted a window) and a state-of-affairs SA_2 (shards of glass were present on the floor). It is typically between SA_1 and SA_2 that information creation processes (ICPs) took place.

[10] Other connections are also possible, notably formal connections such as deductions or inductions (including inferences to the best explanation and analogies).

[11] Here, I considerably simplify the science for the sake of brevity, focusing on the iridium anomaly. Other pieces of evidence played a critical role, notably the discovery of the Chicxulub crater and the presence of shocked quartz and tektites in surrounding areas. For a review, see for instance (Schulte et al., 2010).

[12] Note that whether such a principle appears reasonable or not strongly depends on context. While it is likely non problematic to assume that the laws of physics also applied to pre-historic humans, it is more delicate to transpose present socio-cultural theories (even when established on isolated cultures) to pre-historic times. Similarly, it is also not obvious that current physics can properly be transposed to the very early instants of the universe.

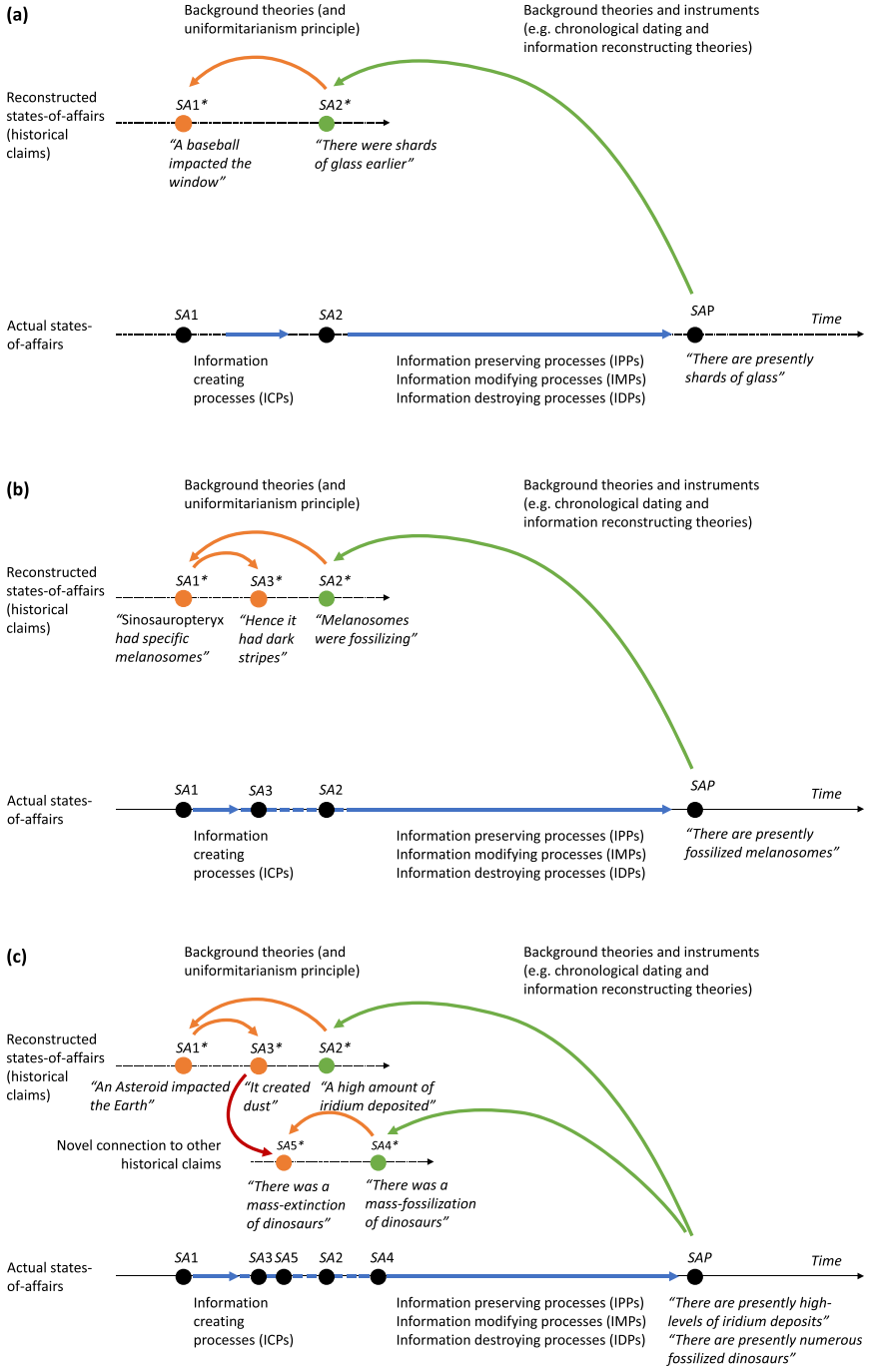

Fig. 2 Model of historical claim justification applied to different cases, from simple to more complex: **a** The toy example of the broken window. **b** The color of *Sinosauropteryx* feathers. **c** The asteroid origin of the K-P mass extinction

Yet, as time flowed, information destroying processes (IDPs) occurred, in conjunction with information preserving and information modifying processes (IPPs and IMPs), leading to a present state-of-affairs SA_p (I can see shards of glass). The methods of the historical sciences work backward. They use information extracted from the present state-of-affairs SA_p to reconstruct a past state-of-affairs SA_2^* (the glass shattering took place sometimes in the morning) with the assistance of a first set of background theories, notably CDTs and IRTs. They then infer further statements about another reconstructed state-of-affairs SA_1^* (a baseball impacted the window and shattered it) and its causal connection to SA_2^* with the assistance of yet another set of background theories drawn from the set of all presently available scientific theories relevant to the field of inquiry, and with the assumption that these theories held in the past. Of course, actual scientific cases are more intricate. For instance (Fig. 2b), the case of the color of *Sinosauropteryx* involved finding present fossilized microstructures (SA_p), inferring the fossilization of melanosomes (SA_2^*), hence the presence of specific melanosomes in living *Sinosauropteryx* (SA_1^*) and thereby the dark stripes it displayed (SA_3^*). Similarly, the case of the asteroid impact theory, even when simplified into a working example, mobilized similar and other sets of inferences (Fig. 2c).[13]

While historical claims can be construed as more or less complex sets of interconnected statements about the past, their justification involves a broader network of motivated inferences. For instance (Fig. 2a), the justification of the claim consisting of the two factual statements SA_1^*, SA_2^*, and their causal connection, depends on the evidence and theoretical support granted to each one of these statements, which in turn rely on statements about present states of affairs (SA_p) and diverse background theories used to infer each one of the factual and connection statements. As an increasing number of statements about the past get assembled into more complex historical claims—possibly up to the point where they will be considered as narratives—, their justification will mobilize an even broader set of elements.

For the sake of the present argument about granularity, I will consider simplified cases where the justification network reduces to a relatively simple chain of inferences. What matters is that justification relies on a minimal number of necessary constituents, from traces in present states-of-affairs to inferred past states-of-affairs, relationships between these states-of-affairs and the use of diverse background theories at different points. The conclusion we reach will carry over to more complex cases.

5 Epistemic granularity in historical claim justification

With this model at hand, we can analyze where and how questions of granularity arise. Intuitively, every single step involved in the formulation and justification of historical claims is subject to granularity choices. Take the extraction of information from a present

[13] Complexifying the schema even further, one may also consider cases where the historical investigation takes place over an extended period of time with different ICPs, IDPs, IPPs and IMPs occurring during that very period of investigation, possibly affecting the information that was extracted at start. In other words, all information affecting processes not only take place in "phenomena-time" but also in "data-time", to take Leonelli's terminology (Leonelli, 2016). For an example of how data-time matters in historical inquiry, see (Currie, 2021).

state-of-affairs SA_P: that information is formulated at a certain granularity, which includes or not certain details. For instance, I may summarize the state of my kitchen window, when coming home, in different ways, from "the window is broken" to "there is a fairly circular 5 cm-wide hole in the window with radial fractures while shards of glass are scattered on the floor at an average distance of 2 m for the window and a baseball with a distinctive heart-shape marking encircling the names "Sue" and "Denis" rests in one corner; furthermore my neighbor saw that the glass was already broken at noon time".

I use here the notion of granularity in an intuitive or pragmatic way, to characterize the level of detail of the chosen description of an item of interest, typically by contrast with other possible levels of detail (coarser or finer grained).[14] This is not to say that a formal account of granularity cannot be proposed. In his numerous contributions to fuzzy logic, Lotfi Zadeh proposed a "theory of fuzzy information granulation" while arguing that granulation—the act of describing items at a certain granularity—played a central role in human reasoning, on par with causation (Zadeh, 1997). This view is notably found in granular computing theory (e.g., Yao, 2008), where a taxonomy of types of granularities has been proposed, that highlights different principles for individuating grains or granules, such as scale- or non-scale-dependency, aggregation, resolution, structural/spatial relation or folding (Keet, 2006). Building on these works, I will define epistemic granularity as follows:

> (EG) Epistemic granularity is the condition for knowledge propositions of being formulated with specific grains, each grain consisting of a possible description chosen among hierarchically embedded and equally valid alternative descriptions.

So construed, epistemic granularity presupposes a hierarchical granular perspective with at least two levels of descriptions, and where a finer-grained level contains knowledge that is more detailed than its adjacent coarser-grained level. Within this perspective, any granular level can be referred to as grain size. A granular perspective captures a specific view about how levels are meant to relate to one another (such as aggregation or scale). Since a knowledge proposition typically includes different components that can each be described at different grains, a granular perspective also presupposes a certain homogeneity between the grain levels of its different components, and a relevance of these grain levels for a certain epistemic question or context.

Consider the toy example of the broken window with its central claim formulated as: "A baseball smashed the window in my kitchen at around 11:00 am". Granular perspectives are possible for all major components of such a sentence: (i) the subject or entity that is the focus of the sentence can be described, from coarser to finer levels, as: "something or someone", "a projectile", "a ball", "a baseball", "a baseball with a heart marking"; similarly, (ii) the action that concerns the subject can be formulated as "smashed", "made a circular impact bordered by fractures", "made a circular impact bordered by fractures, with a speed of 100 km/h and an angle of 90°"; (iii) the entity impacted by the action may be described as: "my window", "my kitchen window", "my double-pane kitchen window made of 3 mm thick glass";

[14] This intuitive usage is also the case for most of the examples mentioned in footnote 2.

and so can (iv) spatiotemporal elements as: "today", "sometimes between 9:30 and 12:00", "around 11:00" etc.[15]

While finer-grained descriptions will include more information and will entail coarser-grained descriptions (given a specific granular perspective), more information does not necessarily mean finer-grain level, notably when irrelevant elements are conjoined with any knowledge proposition.[16]

In historical claim justification, granularity affects the formulation of the different states-of-affairs that are mobilized (as we just saw). It also manifests itself in the background theories that are used to justify inferential links between these different states-of-affairs. A common-sense qualitative version of classical mechanics, for instance, will lead to much coarser inferences (such as a rough estimate of the direction of the impacting ball) compared to a precise quantitative version (which may predict more accurately the direction and speed of the ball and where it was struck). Still the use of glass fracture analytical techniques—as is done in forensic science (e.g., Caddy, 2001)—would reveal unsuspected details about the force and direction of a projectile, leading to finer-grained formulations of the triggering event than just relying on common-sense experience. Similarly, different chronological dating theories involve different levels of uncertainties and enable more or less fine-grained dating of past states-of-affairs.

As made explicit by the proposed model of historical claim justification, any historical claim relies on a network of individual factual statements (from traces extracted from present states-of-affairs to inferred past states-of-affairs) and connecting statements resulting from the application of a diversity of background theories (i.e., CDTs and IRTs). Since these statements and these background theories are all subject to granularity, the resulting historical claims are also subject to granularity. This is to say that historical claims are always formulated and—most importantly—justified at a certain granularity which depends on the way past states-of-affairs are described as well as the inferences with which they are connected to one another. Typically, the granularity of inferred statements about the past will be at least as coarse as the coarser granularity of the statements and background theories of the justification network.[17] More generally, whether claims are justified by evidence depends on whether the epistemic granularity of the statements and background theories required to infer these claims make possible such justification.

[15] Historical statements may use bivalent predicates (e.g., alive vs. dead), in which case it might be argued that no alternative descriptions are available at alternative granularities (as with the sentence "he is dead"). Yet historical claims are usually more complex, notably with temporal elements that can be described at different granularities, depending on context and relevance (e.g., compare "he was found dead" with "he was found dead between ten and ten thirty last night" in a murder case).

[16] Consider: (*A*) "A baseball smashed the window in my kitchen at around 11:00 am"; (*B*) "A baseball smashed the window in my kitchen at around 11:00:07 am"; and (*C*) "A baseball smashed the window in my kitchen at around 11:00 am while a *Sinosauropteryx* was discovered in China". Compared to (*A*), (*B*) includes more information, is finer-grained, and entails (*A*), given a time-based scale-dependency granularity perspective. Yet, (*C*) which includes also more information than (*A*) and entails (*A*), is not finer grained compared to (*A*).

[17] I believe this should be the case of simple historical claims where the justification chain is linear (as depicted in Fig. 2). In more complex cases, the granularity of inferred statements may actually depend on the topology of the justification network. For instance, it might be the case for some coarse-grained inferential link between two statements to be circumvented by finer-grained inferences mediated by other statements. This is left for further investigations.

Besides such constraints imposed by the justification network, at least three sets of factors intervene in grain choice. First, pragmatic factors. Researchers interests unmistakably contribute to the general framing of research questions, hence influence the granularity of hypotheses and possible claims (even if my insurance company will not care much whether the window braking was accidental or not, I may be interested in knowing more about the circumstances of its shattering so as to evaluate whether it may happen again, whether it constitutes a threat and so forth; as a result, I may formulate my questions with a finer granularity than my insurance company). Similarly, the instruments and background theories that are available to research teams at certain points in time certainly influence the granularity at which evidence and statements are formulated (mobilizing microscopic investigation of glass fragments and glass fracture theories as in the best of forensic science will undoubtedly lead to finer grain formulations of present and past states-of-affairs compared to my unexpert visual inspection).

The granularity of historical claims is further constrained by epistemic factors that concern evidence accessibility and theory availability. Present evidence about past states-of-affairs may have different accessibility statuses: while some evidence is already accessed (data that we could find and read, for instance shards of glass on the floor), other evidence is accessible though not yet accessed (data that we would be able to read if we were to find it but that we haven't found yet, such as the baseball hidden behind the trash can), still other evidence is currently not accessible given available instruments and background theories (data that we are not currently able to find nor read but that we would be able to find and read given new background theories and instruments; think of the detailed patterns of glass shards that, to the best of my knowledge, we are still unable to use to make inferences about the exact speed and direction of the impacting ball). Furthermore, currently available background theories certainly limit the granularity at which statements about the past can be inferred (on the basis of accessed present evidence) as well as the granularity of inferred relations between such statements.

Finally, this granularity is also constrained by empirical factors that concern the extent to which different types of information creating, preserving, modifying, or destroying processes (ICP, IPP, IMP and IDP) have actually taken place, possibly offsetting one another. The relative significance of the interplay between these processes and the ultimate outcome of this interplay are indeed an empirical matter that differs from case to case and that can also contribute to cases of either overdetermination or local underdetermination (OD or LU). As recognized by Turner (2016), there is no general rule about whether either of these two should prevail.

6 Epistemic granularity in OD and LU cases

Both overdetermination and local underdetermination are relational properties: they concern the epistemic status of a specific claim about the past relative to a justification network of inferred statements, evidence, and background theories. Since all

these elements are grain-relative in the sense that their formulation relies on specific choices of granularity as I just described (Section 5), it should come as no surprise that OD and LU are also grain-relative: OD cases concern historical claims (formulated at a certain grain) that are overdetermined by their justification networks (which include diverse statements and background theories formulated at specific grains too); and similarly, LU cases concern historical claims (formulated at a certain grain) that are undetermined by any current justification network (which also includes diverse statements and background theories formulated at specific grains). Consequently, there can be OD of a certain historical claim relative to a certain justification network (formulated at a certain grain) but no such OD when things are formulated at a different epistemic grain. The same goes for LU.

This can be illustrated with historical claims that consist of a single statement (see Fig. 3). For instance, there is OD of the historical claim SA^*-G_4 (read: the claim SA^* described at the epistemic granularity 4) by present evidence when the latter is formulated as SA_p-G_4 (or any SA_p-G_i for $i \geq 4$) together with background theories BT-G_4 (or any BT-G_i for $i \geq 4$). Yet, there is no OD of SA^*-G_4 by any combination of SA_p-G_j and BT-G_j with $j < 4$. Quite the contrary, it is LU that then characterizes the epistemic status of SA_p-G_4 as inferred from SA_p-G_j and BT-G_j with $j < 4$.

In cases where historical claims consist of multiple interconnected statements (e.g., a more or less complex narrative), their status as OD or LU can be extrapolated from the OD or LU statuses of their constitutive statements, which in turn depend both on their granularity and the granularity of the elements that enter into their justification networks. Though this may depend on the case at hand—and notably on possible inferential redundancies between elements—a reasonable rule of thumb would be to consider that such claims are LU as soon as any of their constitutive statements is LU, and conversely, to define their status as OD only when all their constitutive statements are OD.[18]

Another way to look at the relational status of OD and LU is to understand that, given a certain granularity of evidence and background theories—say SA_p-G_6 and BT-G_6 as in Fig. 3—OD provides justification for any historical claim of a granularity at least as coarse as that of SA^*-G_6. In other words, one way to guarantee that OD obtains is to make sure that one can rest content with historical claims that are formulated at a coarser grain level compared to the evidence and background theories one has access to. Conversely, requiring that historical

[18] A specific question could be raised about the OD or LU status of colligatory claims, i.e., claims that rely on colligatory concepts, which are argued to play a significant role in historical narratives. Answers will be highly dependent on the views one adopts about such concepts in terms of their definition and justification. For instance, if colligatory concepts are taken to bind facts together through an idea and therefore to "fit the facts" or represent them (Walsh, 1974; Ankersmit, 1995; McCullagh, 2009), then the hierarchical granular perspective will be satisfied and the justification of the colligatory claims will result from the justification of the individual statements about these facts and their being OD or LU. If, on the other hand, colligatory concepts are taken to only be in the historian's mind, reflecting a specific interpretation and lacking truth conditions (Jenkins, 1995; Kuukkanen, 2015), then either the question whether colligatory claims are OD or LU is meaningless, or all colligatory claims are underdetermined, depending on whether the hierarchical granular perspective holds or not (for instance due to vagueness or the addition of a personal interpretation).

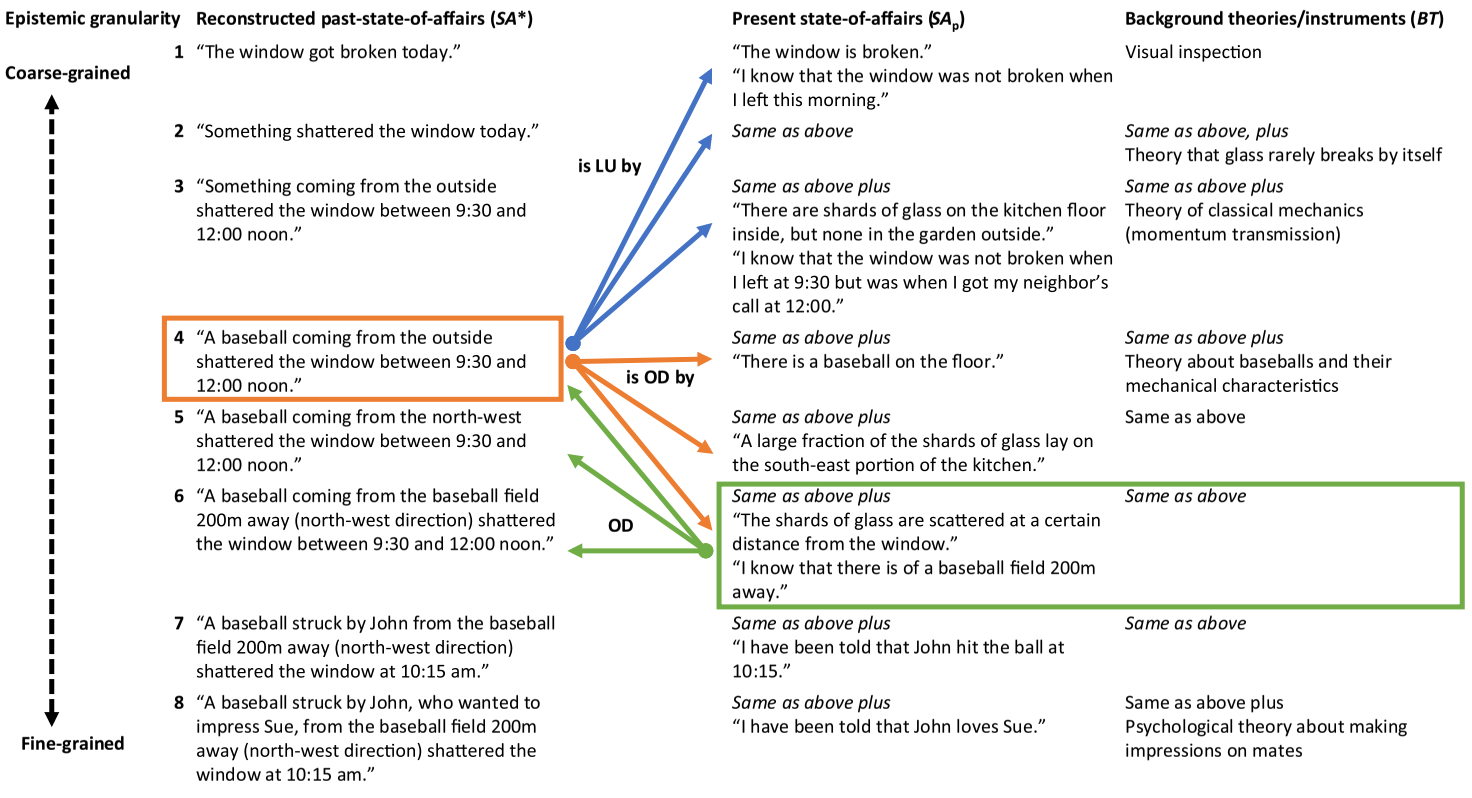

Fig. 3 Relational properties of OD and LU depending on the relative granularity of historical claims, accessed evidence and background theories. For the sake of simplicity, finer granularity is here illustrated by adding details to higher grained statements; yet this needs not always be the case: some statements may be finer grained with respect to some aspects (e.g., temporal precision) but not to some others (e.g., special localization)

claims be formulated at a finer grain will almost assuredly result in LU by presently accessed evidence and available background theories. As a result, changes in epistemic grain anywhere in the justification network will affect the relevance of OD or LU for specific claims.

Epistemic granularity thereby sheds light on how researchers negotiate around LU issues, seize OD opportunities, or produce novel LU questions. For instance, when facing an LU issue, say of SA^*-G_i on the basis of SA_p-G_m and BT-G_x, a typical strategy is to try and move to finer-grained evidence SA_p-G_n with $n > m$ and background theories BT-G_y with $y > x$. This is exactly what happened in the case of the colors of *Sinosauropteryx* feathers: the claim about this color SA^*-G_i was initially locally underdetermined by available evidence SA_p-G_m stemming from fossilized remains of *Sinosauropteryx* and background theories BT-G_x about which information to infer from these remains. Adopting novel background theories BT-G_y with $y > x$ about melanosome fossilization and about melanosome color theory made it possible to reformulate the present evidence at a finer grain SA_p-G_n with $n > m$, then leading to a justified inference about the color of *Sinosauropteryx* SA^*-G_i. Similarly, in the case of the K-Pg mass-extinction, many of the novel questions that may arise are finer-grained reformulations of the currently inferred statements describing past states-of-affairs and their relationships. Tapping into finer-grained evidence or background theories makes possible to overcome LU. Conversely, reformulating claims or hypotheses at a finer-grain creates novel LU cases on the basis of claims formerly characterized by OD, while reformulating at a coarser-grain claims or hypotheses that currently face LU is a means of recovering justified claims (though with less detailed information compared to what was initially sought after).

This means that, given a minimal amount of evidence and background theories, something can always be said about the past at a certain epistemic granularity.[19] As a consequence, not all claims about a given past state-of-affairs at all grain levels are locally underdetermined. Furthermore, not all claims about a given past state-of-affairs at all grain levels are overdetermined. Hence the key role played by epistemic granularity in framing and justifying historical claims.

7 Granularity in the dynamics of historical claims

Not only does epistemic granularity play a role in OD- and LU-statements, it also sheds light on one of the many ways historical inquiry may move forward. Indeed, debates about historical claims are sometimes framed as concerning the justification strength of these claims on the basis of smoking guns (as OD proponents would have it). At other times, historical debates are framed as consisting in setting limits to historical quests and identifying unanswerable questions (as LU proponents may insist). Still others may demand that historical debates concern choices between

[19] This also implies that shifting to finer-grained claims need not be an end in itself (Jackson & Pettit, 1992).

strikingly incompatible rival claims: the asteroid vs. volcanic hypotheses of K-Pg mass extinction is one such well-known example (Keller, 2012). But it would be inaccurate to claim that all debates in the historical sciences take such form. Many debates hinge on questions of epistemic granularity.

Currie examined one such case where coarser-grained claims, once established, may serve as scaffolds from which novel evidence can be found to arbitrate between rival finer-grained hypotheses (Currie, 2018, chap. 10).[20] Yet again, not all questions of granularity in historical investigation are about arbitrating between alternative finer-grained hypotheses. Take the case of the color patterns of *Sinosauropteryx* feathers. The debate at stake was not to establish one particular fine-grained claim about these color patterns as opposed to another rival fine-grained claim about different color patterns: it was to explain the presence of sub-micron bodies, which were interpreted as melanosomes, thereby resulting in a depiction of *Sinosauropteryx* that included color patterns (as opposed to a coarser uncolored depiction of that dinosaur) (Zhang et al., 2010). In other words, it was about establishing a finer-grained description of this dinosaur (a description that included feather color), as opposed to just having a coarser-grained description (without feather color).

Research on the K-Pg mass extinction also includes such granularity-based debates: How much of the extinction can be attributed to the asteroid impact itself vs. to the volcanism that followed (Renne et al., 2015)? Which asteroid-triggered events actually caused the mass-extinction: a heat/fire effect followed by an impact winter (Robertson et al., 2013), the amount of dust emitted in the atmosphere that would have blocked nearly all photosynthesis (Pope et al., 1998), the production of sulfuric acid aerosols and acid rains (Ohno et al., 2014)? Which clades were the most impacted, to which extent and in which successive stages (e.g., Longrich et al., 2011)? And so forth. As noted by Forber and Griffith (2011), stronger or weaker versions of the impact theory can be formulated. These different versions depend on finer-grained descriptions of the reconstructed past states-of-affairs.

Such examples highlight the fact that much historical investigation does not take the form of establishing claims once-and-for-all, with fixed descriptions, but includes numerous shifts in epistemic granularity and claim formulation. In other words, historical investigations are not just of the form "justifying SA^{*} on the basis of SA_{p} (in contrast to SA^{**} on the basis of SA_{p})" but also —and I would say mostly— of the form "justifying SA^{*}-G_{i} on the basis of SA_{p}-G_{m} (in contrast to SA^{*}-G_{j} on the basis of SA_{p}-G_{n})". This is to say that much of the justification dynamics that is at work in the historical sciences actually concerns negotiations over epistemic granularity. Such epistemic granularity view stresses the roles that changes in epistemic granularity play in establishing the justificatory basis for given claims.

[20] Cases of scaffolding, Currie argues, are one reason, among several others, for optimism in the historical sciences. Note that the scaffolding metaphor as related to historical investigation has been used elsewhere in a broader sense, as encompassing all the assumptions, background knowledge and technical resources that make possible the use of traces as evidence (Chapman & Wylie, 2016; Wylie, 2017). For a review of the scaffolding metaphor and its different construals, see (Routledge, 2021).

8 Conclusion

As I hope to have shown, the debate between the overdetermination and underdetermination views of historical investigation (and therefore about reasons for optimism vs. pessimism) is rooted in the framing of historical claims at specific granularities. Analyzing this debate led us first to consider a taxonomy of types of information-affecting processes that influence the remaining presence of information about past events (namely information creating, preserving, modifying, and destroying processes). It also led us to envision a model of historical claim justification mapping out the different elements that enter the justification of any historical claim (with the specification of different states of affairs, theories used at different stages in the inferential network, and inferences between states of affairs). With this model at hand, I proposed a notion of epistemic granularity and explained how granularity makes its way into the different elements of the justification network, thereby affecting the justification of the overall historical claims. Since overdetermination and underdetermination concern statements about the status of specific claims relative to specific justification networks, granularity changes both in the claims and in the justification networks explain changes in the relevance of either perspective. This epistemic granularity view of historical claims accounts for the shifts that are observed from cases of overdetermination to cases of underdetermination, and vice-versa. The proposed model of historical claim justification, and the role played by granularity within its different components also make it possible to understand the dynamics of historical investigation. Though likely relevant in other domains of science—notably domains in which knowledge is qualitative or relies on fuzzy concepts—epistemic granularity appears as a central, and often implicit, feature of the dynamics of knowledge justification in the historical sciences.

Acknowledgements The author thanks the audience of the *Modeling the Possible* virtual workshop (2020-2021), notably Natalia Carrillo-Escalera, Gregor Greslehner, Till Grüne-Yanoff, Tarja Knuuttila, Rami Koskinen, Andrea Loettgers, Alan Love, and Paul Teller for feedback. Thanks also to Adrian Currie and Derek Turner for comments on an earlier version of the manuscript, and to two anonymous reviewers for the *EJPS*. Funding from Canada Research Chairs (CRC-950-230795) is gratefully acknowledged.

Data Availability This study does not analyse or generate any datasets since it proceeds within a theoretical philosophical approach. Relevant material can be obtained from the cited references.

Declarations

Competing interests The author has declared that no competing interests exist.

References

Alvarez, L. W., Alvarez, W., Asaro, F., & Michel, H. V. (1980). Extraterrestrial cause for the cretaceous-tertiary extinction. *Science, 208*(4448), 1095–1108. https://doi.org/10.1126/science.208.4448.1095

Ankersmit, F. R. (1983). *Narrative logic: A semantic analysis of the historian's language* (Vol. 7). Martinus Nijhoff Publishers.

Ankersmit, F. R. (1995). Statements, texts and pictures. In F. R. Ankersmit & H. Kellner (Eds.), *A new philosophy of history* (pp. 212–240). Reaktion Books.

Bourrat, P., & Charbonneau, M. (2022). Grains of description in biological and cultural transmission. *Journal of Cognition and Culture, 22*(3–4), 185–202. https://doi.org/10.1163/15685373-12340131

Buskell, A., & Currie, A. (2021). Uniqueness in the life sciences: How did the elephant get its trunk? *Biology & Philosophy, 36*(4), 37. https://doi.org/10.1007/s10539-021-09811-4

Caddy, B. (Ed.). (2001). *Forensic examination of glass and paint analysis and interpretation*. Taylor & Francis.

Cartwright, N. (2020). Middle-range theory. *Theoria: An International Journal for Theory, History and Foundations of Science, 35*(3), 269–323. https://doi.org/10.1387/theoria.21479

Chapman, R., & Wylie, A. (2016). *Evidential reasoning in archaeology*. Bloomsbury Academic.

Cleland, C. E. (2002). Methodological and epistemic differences between historical science and experimental science. *Philosophy of Science, 69*(3), 447–451. https://doi.org/10.1086/342455

Collins, J. (2014). Cutting it (too) fine. *Philosophical Studies, 169*(2), 143–172. https://doi.org/10.1007/s11098-013-0163-1

Currie, A. (2018). *Rock, bone and ruin*. MIT Press.

Currie, A. (2021). Stepping forwards by looking back: Underdetermination, epistemic scarcity and legacy data. *Perspectives on Science, 29*(1), 104–132. https://doi.org/10.1162/posc_a_00362

Currie, A., & Sterelny, K. (2017). In defence of story-telling. *Studies in History and Philosophy of Science Part A, 62*(April), 14–21. https://doi.org/10.1016/j.shpsa.2017.03.003

Dretske, F. I. (1977). Referring to events. *Midwest Studies in Philosophy, 2*, 90–99. https://doi.org/10.1111/j.1475-4975.1977.tb00030.x

Forber, P. (2009). Spandrels and a pervasive problem of evidence. *Biology & Philosophy, 24*(2), 247–266. https://doi.org/10.1007/s10539-008-9144-8

Forber, P., & Griffith, E. (2011). Historical reconstruction: Gaining epistemic access to the deep past. *Philosophy & Theory in Biology*, *3*(August). https://doi.org/10.3998/ptb.6959004.0003.003

Goudge, T. A. (1967). *The ascent of life*. University of Toronto Press.

Havstad, J. C. (2019). Metaphorical ripples. *Philosophy, Theory, and Practice in Biology*, *11*. https://doi.org/10.3998/ptpbio.16039257.0011.010.

Hitchcock, C. (2012). Events and times: A case study in means-ends metaphysics. *Philosophical Studies, 160*(1), 79–96. https://doi.org/10.1007/s11098-012-9909-4

Hull, D. L. (1981). Historical narratives and integrating explanations. In L. W. Sumner & F. Wilson (Eds.), *Pragmatism and purpose: essays presented to Thomas A. Goudge* (pp. 172–88). University of Toronto Press.

Jackson, F., & Pettit, P. (1992). In defense of explanatory ecumenism. *Economics and Philosophy, 8*(1), 1–21. https://doi.org/10.1017/S0266267100000468

Jeffares, B. (2008). Testing times: Regularities in the historical sciences. *Studies in History and Philosophy of Science Part c: Studies in History and Philosophy of Biological and Biomedical Sciences, 39*(4), 469–475. https://doi.org/10.1016/j.shpsc.2008.09.003

Jenkins, K. (1995). *On "what is history?": From Carr and Elton to Rorty and White*. Routledge.

Keet, C. M. (2006). A taxonomy of types of granularity. In *2006 IEEE International Conference on Granular Computing*, (pp. 106–11). IEEE. https://doi.org/10.1109/GRC.2006.1635767

Keller, G. (2012). The cretaceous–tertiary mass extinction, Chicxulub impact, and Deccan volcanism. Earth and Life. In J. A. Talent (Ed.), *Earth and life: Global biodiversity, extinction intervals and biogeographic perturbations through time* (pp. 759–93). Springer.

King, J. C. (2013). On fineness of grain. *Philosophical Studies, 163*(3), 763–781. https://doi.org/10.1007/s11098-011-9844-9

Kleinhans, M. G., Buskes, C. J. J., & De Regt, H. W. (2005). *Terra Incognita*: Explanation and reduction in earth science. *International Studies in the Philosophy of Science, 19*(3), 289–317. https://doi.org/10.1080/02698590500462356

Kosso, P. (1993). Middle-range theory in historical archaeology. *Studies in History and Philosophy of Science, 24*(2), 163–184. https://doi.org/10.1016/0039-3681(93)90044-K

Kuukkanen, J.-M. (2015). *Postnarrativist philosophy of historiography*. Palgrave Macmillan UK. https://doi.org/10.1057/9781137409874

Leonelli, S. (2016). *Data-centric biology*. University of Chicago Press.

Lewis, D. (1979). Counterfactual dependence and time's arrow. *Noûs, 13*(4), 455–476. https://doi.org/10.2307/2215339

Longrich, N. R., Tokaryk, T., & Field, D. J. (2011). Mass extinction of birds at the Cretaceous-Paleogene (K–Pg) boundary. *Proceedings of the National Academy of Sciences, 108*(37), 15253–15257. https://doi.org/10.1073/pnas.1110395108

Malaterre, C. (2024). Is life binary or gradual? *Life, 14*(5), 564. https://doi.org/10.3390/life14050564

McCullagh, C. B. (2009). Colligation. In A. Tucker (Ed.), *A companion to the philosophy of history and historiography* (pp. 150–61). Wiley-Blackwell.

O'Hara, R. J. (1992). Telling the tree: Narrative representation and the study of evolutionary history. *Biology & Philosophy, 7*(2), 135–160. https://doi.org/10.1007/BF00129880

Ohno, S., Kadono, T., Kurosawa, K., Hamura, T., Sakaiya, T., Shigemori, K., Hironaka, Y., et al. (2014). Production of sulphate-rich vapour during the chicxulub impact and implications for ocean acidification. *Nature Geoscience, 7*(April), 279–282. https://doi.org/10.1038/ngeo2095

Page, M. D. (2021). The role of historical science in methodological actualism. *Philosophy of Science, 88*(3), 461–482. https://doi.org/10.1086/712833

Pope, K. O., Baines, K. H., Ocampo, A. C., & Ivanov, B. A. (1997). Energy, volatile production, and climatic effects of the Chicxulub cretaceous/tertiary impact. *Journal of Geophysical Research: Planets, 102*(E9), 21645–21664. https://doi.org/10.1029/97JE01743

Pope, K. O., D'Hondt, S. L., & Marshall, C. R. (1998). Meteorite impact and the mass extinction of species at the cretaceous/tertiary boundary. *Proceedings of the National Academy of Sciences of the United States of America, 95*(19), 11028–11029. https://doi.org/10.1073/pnas.95.19.1102

Raab, L. M., & Goodyear, A. C. (1984). Middle-range theory in archaeology: A critical review of origins and applications. *American Antiquity, 49*(2), 255–268. https://doi.org/10.2307/280018

Renne, P. R., Sprain, C. J., Richards, M. A., Self, S., Vanderkluysen, L., & Pande, K. (2015). State shift in Deccan volcanism at the Cretaceous-Paleogene boundary, possibly induced by impact. *Science, 350*(6256), 76–78. https://doi.org/10.1126/science.aac7549

Robertson, D. S., Lewis, W. M., Sheehan, P. M., & Toon, O. B. (2013). K-Pg extinction: Reevaluation of the heat-fire hypothesis. *Journal of Geophysical Research: Biogeosciences, 118*(1), 329–336. https://doi.org/10.1002/jgrg.20018

Routledge, B. (2021). Scaffolding and concept-metaphors: Building archaeological knowledge in practice. In A. Killin & S. Allen-Hermanson (Eds.), *Explorations in archaeology and philosophy* (pp. 433:47–63). Springer International Publishing. https://doi.org/10.1007/978-3-030-61052-4

Schulte, P., Alegret, L., Arenillas, I., Arz, J. A., Barton, P. J., Bown, P. R., Bralower, T. J., et al. (2010). The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. *Science, 327*(5970), 1214–1218. https://doi.org/10.1126/science.1177265

Sober, E. (1988). *Reconstructing the past: Parsimony, evolution, and inference*. MIT Press.

Strawson, P. F. (1985). Causality and explanation. In B. Vermazen & M. Hintikka (Eds.), *Essays on Davidson: Actions and events* (pp. 115–136). Clarendon Press.

Tamborini, M. (2020). Technoscientific approaches to deep time. *Studies in History and Philosophy of Science Part A, 79*(February), 57–67. https://doi.org/10.1016/j.shpsa.2019.03.002

Tucker, A. (1998). Unique events: The underdetermination of explanation. *Erkenntnis 48*, 59–80. https://doi.org/10.1023/A:1005315532171

Tucker, A. (2011). Historical science, over- and underdetermined: a study of Darwin's inference of origins. *The British Journal for the Philosophy of Science, 62*(4), 805–829. https://doi.org/10.1093/bjps/axr012

Turner, D. D. (2005). Local underdetermination in historical science. *Philosophy of Science, 72*(1), 209–230. https://doi.org/10.1086/426851

Turner, D. D. (2007). *Making prehistory: Historical science and the scientific realism debate. Cambridge studies in philosophy and biology*. Cambridge University Press.

Turner, D. D. (2009a). Beyond detective work: Empirical testing in paleontology. In David Sepkoski & Michael Ruse (Eds.), *The paleobiological revolution: Essays on the growth of modern paleontology.* University of Chicago Press.

Turner, D. D. (2009b). How much can we know about the causes of evolutionary trends? *Biology & Philosophy, 24*(3), 341–357. https://doi.org/10.1007/s10539-008-9139-5

Turner, D. D. (2016). A second look at the colors of the dinosaurs. *Studies in History and Philosophy of Science Part A, 55*(February), 60–68. https://doi.org/10.1016/j.shpsa.2015.08.012

Walsh, W. H. (1974). Colligatory concepts in history. In P. L. Gardiner (Ed.), *The philosophy of history* (pp. 127–44). Oxford University Press. http://archive.org/details/philosophyofhist00patr

White, H. V. (1973). *Metahistory: The historical imagination in nineteenth-century Europe*. Johns Hopkins University Press.

Wilkins, J. F., & Godfrey-Smith, P. (2009). Adaptationism and the adaptive landscape. *Biology & Philosophy, 24*(2), 199–214. https://doi.org/10.1007/s10539-008-9147-5

Wylie, A. (2002). *Thinking from things: Essays in the philosophy of archaeology*. University of California Press.

Wylie, A. (2017). How archaeological evidence bites back. *Science, Technology, and Human Values, 2*(42), 203–225. https://doi.org/10.1177/0162243916671200

Wylie, A. (2020). Radiocarbon dating in archaeology: Triangulation and traceability. In S. Leonelli & N. Tempini (Eds.), *Data journeys in the sciences* (pp. 285–301). Springer International Publishing. https://doi.org/10.1007/978-3-030-37177-7

Yao, Y. (2008). Granular computing: Past, present and future. In *2008 IEEE International Conference on Granular Computing*. https://doi.org/10.1109/grc.2008.4664800

Zadeh, L. A. (1997). Toward a theory of fuzzy information granulation and its centrality in human reasoning and fuzzy logic. *Fuzzy Sets and Systems, 90*(2), 111–127. https://doi.org/10.1016/S0165-0114(97)00077-8

Zhang, F., Kearns, S. L., Orr, P. J., Benton, M. J., Zhou, Z., Johnson, D., Xing, Xu., & Wang, X. (2010). Fossilized melanosomes and the colour of cretaceous dinosaurs and birds. *Nature, 463*(7284), 1075–1078. https://doi.org/10.1038/nature08740

Zhou, Z., Barrett, P. M., & Hilton, J. (2003). An exceptionally preserved lower cretaceous ecosystem. *Nature, 421*(6925), 807–814. https://doi.org/10.1038/nature01420