Quantum Darwinism: Redundant Records of Emergence

Lucy Mason

Abstract

Records frequently appear in explanations of the emergence of classicality from quantum mechanics. Quantum Darwinism in particular argues that the interaction between a system and its environment produces redundant records in the environment. The records allow the state of the system to be determined independently by many observers, which is identified as a key criterion for classicality. This models the emergence of the classical world in an information theoretic framework. This differs from the more commonly used standard for emergence in the philosophy of physics literature which relies on the instantiation of classical dynamics, motivated by the focus on the dynamics of the reduced density matrix in quantum decoherence. The goal of this paper is to examine the use of records in quantum darwinism and show how understanding what a record is allows us to relate the information theoretic emergence described by quantum darwinism to the accounts of the emergence which focus on dynamical laws. This tells us why records play such a central role in emergent classicality.

1 Introduction

The familiar classical world emerges from a fundamentally quantum one. This is commonly assumed to be achieved through the interaction of a system with its environment. The most well-known account is quantum decoherence (see Schlosshauer 2007 for details) which models how the interaction with the environment effectively diagonalizes the reduced density matrix of the system (picking out a preferred basis) and how the resulting state evolves according to classical dynamics. But more recently a different account - coined *quantum darwinism* - has been developed (see Zurek 2009, 2022 for overview).[1] Instead of tracing out the environment to focus on the system, quantum darwinism argues that the interaction with the environment produces redundant records of an observable of the system in the environment. The production of records is used to explain how a pointer basis is selected and the records allow for many observers to independently determine the state without disturbing it. Zurek calls this criteria the "hallmark of classicality" (Zurek 2009, p.182). This is complementary to the standard account of environment-induced decoherence but redefines what emergent classicality means by putting it in the information theoretic framework. It is concerned with what information is available through measurements to different observers.[2]

Philosophical accounts of emergence in science largely focus on the novelty of the higher level theory and how it screens off irrelevant details of the lower level theory to provide more efficient explanatory or predictive power (Woodward 2021; Ross 2000; Ladyman & Ross 2007; Franklin & Robertson 2022).[3] [4] These

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[1] Here I take decoherence to refer specifically to the earlier theories of environment-induced decoherence so as to clearly distinguish them. Often both the established theory and the new development of quantum darwinism are jointly subsumed under the title decoherence theory which is taken to apply to all the ways in which classicality emerges.

[2] This distinction between dynamic approaches and agent focused approaches is explored more in Wallace (2017) where the later is called the inferential approach.

[3] Accounts of emergence developed in the philosophy of physics literature differ from how emergence is considered in other areas such as philosophy of mind. Emergence is considered compatible with reduction and the mathematical and conceptual compatibility of the two theories remains important.

[4] How to make the novelty condition precise is contested. It is sometimes replaced with *autonomy*. Only the screening off condition

background ideas have been developed more specifically for quantum decoherence as a theory of emergent classicality by arguing that as the off-diagonal terms of the reduced density matrix tends towards zero (during interaction with the environment) they become irrelevant to the dynamics of the system and can be treated as effectively zero. Classical dynamics can accurately predict the evolution of the system and this is used to justify the irrelevance of the lower level details (Wallace 2012, Franklin 2022). I will call this the *dynamic account* of emergence which contrasts to the *information account* that quantum darwinism provides.

Due to the shift in focus in quantum darwinism from dynamical laws to information as a standard for classicality it is hard to apply the established philosophical accounts of emergence to this theory. The dynamical laws were essential to justify screening off the irrelevant lower level details and establish an emergent theory. So how can a rigorous sense of emergence be justified in the information account? I will argue here that understanding records in more detail can answer this question by showing that the presence of records is indicative of the screening off condition necessary for emergence. This shows clearly how both the dynamic and information accounts share this common condition and why records are important for understanding the transition to classicality.[5] I will also show how quantum darwinism adds directly to the dynamic account by showing that diagonalization of the density matrix - while necessary - is not sufficient for the robust and stable instantiation of classical dynamics and in certain cases more rigorous screening off, which the presence of records are an indicator of, is needed.

In section 2 I will lay out the theory of quantum darwinism and show, by considering a model of scattering photons off a central atom, how it sets a more rigorous standard for emergent classicality than the diagonalization of the density matrix does. Section 3 will then turn to the general idea of what a record is (independently of their use in quantum mechanics), using an account developed in Mason (2023), where records are seen as correlations that are robust against noise. This account highlights that redundancy is a common feature in many types of records and is used to achieve the necessary robustness. Sections 4 and 5 will then use this to help us understand how the information account and the dynamic account share a common screening off condition. First in section 4 by showing that the redundant records in quantum darwinism are playing the same role of protecting against noise as in the general account of records; this largely involves justifying treating quantum correlations as irrelevant noise. Then in section 5 by considering how robustness against noise corresponds to the screening off condition for emergence.

2 Quantum Darwinism and the Emergence of Classicality

2.1 Quantum Darwinism: A Review

Instead of looking at the dynamics and behaviour of the reduced density matrix, quantum darwinism instead focuses on how a defining feature of classicality is the possibility for objective agreement among observers; this comes from using the information framework to motivate quantum darwinism. Sharing independently verified results is an important component of the scientific method (Adlam 2022 explores this in more depth) and the classical assumption is that the world is made of objects with well defined properties that are determinable through measurements. This is characteristic of the classical world that we as agents are used to operating in. However classical information and measurement differ greatly from their quantum counterparts. In a quantum system a measurement by one observer will disturb the system and other observers will not be able to independently verify the results of the measurement. This is not unheard of in classical systems (measurements always have the capacity to destroy the system), but the problem is far more prevalent and

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will be relevant to this paper so novelty will be assumed.

[5] In addition to quantum darwinism, records are also used in the consistent histories approach to decoherence. I will not discuss this here but the conclusion will note how the ideas laid out here could apply to this approach.

fundamental in quantum mechanics due to the centrality of quantum superposition states. A quantum measurement can collapse a superposition into a single outcome and erase the preexisting state. Superposition states can encode information in a uniquely quantum way. A classical two state system can contain a single bit of information; 0 or 1 corresponding to the two states. A quantum one can contain continuously many superpositions of the two states.[6] This constitutes a striking failure of classicality. Measurements destroy the superposition and this places significant limits - that do not have a classical analogue - on what can be done with a quantum system. Also, a superposition state cannot be determined in the usual classical way of measuring its various properties and putting them together to create a full description of the state.

However, once decohered by the environment, direct measurements of the system are no longer necessary. Instead information can be gained indirectly through measurements on the environment without disturbing the system.[7] This is the central insight of quantum darwinism. Records - which are intuitively understood to be reproductions in a separate system of certain information about a state of a particular system - in the environment make this possible. The non-classical aspects of the superposition are suppressed leaving a well defined set of observable properties accessible through measurements on the environment. Now many observers can perform measurements and expect to get the same information out (about the same well-defined observable). The redundant records in the environment are how this sort of classicality can be achieved. As such tracing out the environment - as is traditionally done in environment-induced decoherence - misses important details. Many observers can measure different fragments of the environment and each get information about the state. The redundancy of records means that any random fragment of the environment an observer measures will contain complete records of the observable. The observers do not directly interact with the system and hence do not disturb it (although the process of record creation transforms the state just as in the standard account of decoherence, but it does not destroy or non-unitarily transform it). They may disturb or destroy the record in their fragment but the redundancy of such records means this does not limit other observers from making the same measurement. This explains how this element of classicality - objective, shared information about the properties of a system - is achieved.

Additionally the mechanism which creates records also explains how the pointer basis is selected. The no-cloning theorem prevents the copying of unknown quantum states so the records cannot contain information on the entire state. Instead what *can* be copied is information about observables. The structure of the environment determines which observable will be most effectively copied and hence selects this as a pointer basis; the copying reinforces this observable and suppresses other possible bases. This is the motivation for the name *darwinism*: states that reproduce themselves most effectively are the fittest for survival. Furthermore what makes a record informative is when the record system has a number of different possible states, and each of them corresponds (to some degree of faithfulness) to a different state of the system being recorded. The possible states of the record must be differentiable and a measurement must tell you which of the possible states it is in so that an inference about the corresponding state of the system can be made. This clearly limits records to orthogonal states which can be measured by a projector or POVM measurement.

That role that records play here is essential. The state cannot be measured directly without perturbing it and removing the chance for other observers to independently verify the result. Records provide a means to access the information without touching the state directly. The production of records therefore creates a particular kind of environment state which provides indirect access to the classical subset of the total information about the state. This defines the emergent classical state that we are looking for. Additionally it is not just the presence of a single record but the redundancy of them that is important so as for allow multiple observers to

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[6] This does not straightforwardly mean that a quantum states can encode infinitely more information. This is limited by measurement procedures and what can be extracted. Timpson (2013) explores this in detail.

[7] This presentation may sound as if it is creating a sharp distinction between observer systems and environment systems. This distinction is debated and controversial. However it is not essential to quantum darwinism for there to be this distinction. In reality they can be exactly the same type of systems, and observers can be seen as extensions of the environment.

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2.2 Beyond Diagonalization of the Density Matrix

With the account of quantum darwinism in mind we can see how it sets a more stringent standard for classicality than decoherence based on the effective diagonalization of the density matrix. Normally the latter is taken as the key indicator for when a system can be modelled under classical dynamics (hence fulfilling the dynamic account of emergence). But a case study of scattering a single photon off an atom versus scattering multiple photons reveals that there are cases where this connection is unclear and quantum darwinism is a more rigorous standard for identifying the instantiation of classical dynamics.[8] This result makes it important that our accounts of emergence are not reliant merely on diagonalization and that records can equally be used as an indicator.

Photons scattered off a central atom in a position superposition decohere the atom and encode information about its decohered position. In the case of scattering with a single photon it is not clear how we should regard the final state of the atom. If the photon has the appropriate wavelength (roughly corresponding to the distance between the two states of the superposition) then the photon becomes strongly correlated to the atom and the reduced density matrix of the atom is effectively diagonalized. This is considered a case of decoherence in Wallace (2012) and Joos *et al* (2013). In both cases the single photon case is considered only briefly and then disregarded in favour of analysing in more depth the multiple photon case. Early work on showing how the classical master equation could model the resultant dynamics was not applicable at the small length scale necessary for single photon decoherence but later results made this possible (Gallis & Fleming 1990). So the atom *can* be shown to follow classical dynamics; however while this is technically possible the situation is very unstable. It would be relatively easy for the photon to re-interact and unentangle from the atom, reversing the process of decoherence. It would also be easy for the atom-photon correlation to be disturbed in some way and the dynamics of the reduced density matrix with the photon traced out would not be representative of the state of the atom. Any expected classical behaviour of the atom, if it arises at all, is likely to be short lived and unstable. This does not match with the robust and stable classical world we are familiar with and calls into question whether we can truly justify screening off the full quantum state of the system. Unstable dynamics mean that the photon and the off-diagonal terms of the density matrix are not truly irrelevant to the future evolution of the atom system.

Moving to the framework of quantum darwinism, it is not clear that a single photon would allow an observer to determine the position of the atom (and it definitely would not allow multiple observers to do so). Extracting information from it would be a considerable technical challenge. It is also true that any attempt to measure the photon would involve interacting it with a measuring device; this interaction - where the complex measuring device would essentially act as an environment - would further decohere the atom-photon system. As such this case is hard to assess under quantum darwinism at all. But removing the technical considerations of performing a measurement to extract information, we can focus just on the idea that the photon is, at least nominally, a record regardless of our ability to read it and show that in the single photon case this is not true. Zurek's (1982) early work on decoherence proved this by looking at interacting a two state system - an atom with excited and ground states - with a system of interest - a spin system which could be up or down. The atom system acts as a measuring apparatus; entangling the two systems should allow us to extract information about the spin through its correlation to the atom state. However Zurek shows that this is not possible and the atom cannot act as a record. This is because the states of the atom system and the spin system can both be independently rewritten in many other bases. For example a spin in the $|\uparrow\rangle$, $|\downarrow\rangle$ basis can be rewritten in the

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[8] This is in agreement with the consistent histories account which also argues that diagonalization is only a minimal condition for classical behaviour and more is needed for a full explanation. This account also uses records as an indicator for a stronger sense of emergence. See the conclusion for more comments.

basis $|{\rightarrow}\rangle = (|{\uparrow}\rangle + |{\downarrow}\rangle)/\sqrt{2}$, $|{\leftarrow}\rangle = (|{\uparrow}\rangle - |{\downarrow}\rangle)\sqrt{2}$. Similarly for the atom system where the basis of ground $|{\eqcirc}\rangle$ and excited $|{\circeq}\rangle$ states can be rewritten as $|+\rangle = (|{\circeq}\rangle + |{\eqcirc}\rangle)/\sqrt{2}$, $|-\rangle = (|{\circeq}\rangle - |{\eqcirc}\rangle)\sqrt{2}$. As such the state of the atom cannot be a record of the spin state; the atom state $|{\eqcirc}\rangle$ could correspond to a spin state of either $|{\uparrow}\rangle$ or $|{\rightarrow}\rangle$ (or any other possible basis) and hence tells us nothing. For it to be a record there must be a correlation within a specific basis. This conclusion can be applied to the case of entanglement between a photon scattered off a central atom. They are entangled but not in an informative way.

Additionally it would be impossible for multiple observers to separately measure the single photon and independently obtain information about the atom. Hence this does not satisfy the standards of quantum darwinism. Putting this all together the single photon scattering fails both the information standard and the dynamic standard of emergence despite the atom having an effectively diagonalized reduced density matrix.

When multiple photons (which can either be energetic enough to each individually strongly entangle with the atom or less energetic such that individually they only weakly entangle with it but collectively they decohere the system) are scattered off the atom then a more complex array of measurements can be performed to locate that atom. And different observers can intercept different sets of photons to independently obtain their results. So the multiple photon case satisfies the information account of emergence.[9] It also satisfies the dynamic account: the possibility of re-interaction (of *all* the photons) or disturbance is negligible when multiple photons are involved and we can expect stable classical dynamics. Zurek (2022) shows that the redundancy of records is equivalent to what he calls redundant decoherence. This is where not just the reduced density matrix of the atom with respect to the environment is diagonalized but also the joint state of any atom-photon pair (tracing out the rest of the photon environment). This corresponds to a correlation in a specific basis (in other words the selection of a pointer basis) and means that the photon is now an informative record. It also means that the atom's density matrix remains diagonalized, and follows classical dynamics, robustly. Even if one photon re-interacts or is disturbed the other photons are sufficient to ensure that the atom still can still be accurately represented by the effectively diagonalized reduced density matrix and follows classical behaviour.

This sort of scenario calls into question whether or not the diagonalization of the system's density matrix is a good indicator that the dynamics are effectively classical in a stable and robust sense and whether it can be used as justification for the irrelevance of lower level details. Quantum darwinism helps to identify cases where classical behaviour is particularly robust and stable beyond just the weak instantiation of classical behaviour that the effective diagonalization of the density matrix ensures. It provides a more stringent standard for when classicality has been achieved and emergence can be justified.

3 What are records?

It is clear that records are playing a key role in quantum darwinism and also, from the previous section, that they add to the dynamic account of emergence by indicating robust classical behaviour. I now turn to look at what a record is so as to start understanding why records can play this role. To do this I will start, in this section, by analysing what a record is more generally and present an account of what features a record requires. This follows an account of records presented in Mason (2023) which shows how being robust against noise is an essential property of records, this is not just an instrumental concern about how records are used but is part of what a record *is*. This account shows that redundancy is a feature of all records that provides the necessary robustness.

Records give information about the past in a different way than retrodiction. In physics the most common

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[9] Quantum darwinism formalises this condition in terms of mutual information measures. Zurek (2009) presents this scattering example.

way to find out about either the past or the future is to take the present state of the world (or a part of it) and evolve it forwards under the dynamical laws to find a final state - prediction - or evolve it backwards to find an earlier state - retrodiction. This process gives information equally about both the past and the future (barring probabilistic laws which complicate matters). The vast majority of our fundamental physical laws are time symmetric and can be applied in both the forwards and backwards time direction. (Although in higher level laws we see asymmetry appearing as a common feature, we still understand how to apply the laws both retrodictively and predictively). In contrast, records are physical systems which encode accurate and often detailed information about a specific part of the past. Retrodiction involves taking the entire, fully detailed present state of a system to find out the entire, fully detailed state of the past while records involve only a limited, localised, system giving limited information about a specific past variable or property (e.g. configuration) of a system. In general the difference is in how directly correlated to the past records are. States used in retrodiction are not correlated to any specific time in either the past or the future; the dynamical laws must be used to calculate anything about any other times. Records are correlated to the state of a system (or some aspect of it) at a particular time. From this, information can be directly extracted about this other time while ignoring the wider state of the system, and the rest of the present state.

The most well-known analysis of records comes from Albert (2000; 2015). He models records as the outcome of a measurement process. This starts with a ready state (a known state in the system's past), the evolution of which can be calculated to find out the expected present state. Either the ready state stays the same or it evolves in a predictable way to give the present state. The expected present state can then be compared with the actual present state of the system and any differences between the two can be attributed to an interaction in the intervening interval. The example Albert gives is that of a billiard ball on a table. If we know that the ball was at rest 10s ago we expect it to remain in this state. If we see that it is now moving, we can infer that something collided with the ball during these 10s. From more detailed information about the ball's current state of motion we can infer details about this collision such as direction and how much momentum the second ball colliding with it had. Hence the current state of the ball forms a record of this collision.

This account provides useful insights into how to think about records and provides a basis for understanding how we make inferences. The most important feature coming out of it is that we identify that the current state is not what we expect it to be and this provides the means to infer something about past events. But the account can be criticised for being highly idealised and not describing how the vast majority of records are used everyday.[10] Take the example of a broken branch which acts as a record of an animal's passing. While this can fit within the ready state by considering a past state of the unbroken branch, we do not seem to need knowledge of any particular past state. Rather we just need the idea of the general evolution of the system and its expected behaviour. Albert's account places too much emphasis on the role of the ready state (he accounts for this by saying that while this is the formal account of records, in practice a faint and foggy sense of this process is implicitly used by us every day without conscious thought about ready states). Albert's account also does not seem to offer us any reason why records should play such an important role in transitioning from quantum to classical.

To make our account of records more explanatory of our practical use of them, it seems that instead of taking the ready state as the key part of this what is actually needed is just being able to identify a deviation from the expected evolution of the system. Ready states are a formal way to identify the expected evolution but in many cases are not necessary. Many systems have stable patterns of evolution which can be easily identified. For the broken branch example our background knowledge of how branches usually operate is more than enough to identify the deviation from the expected unbroken state without the need for a specific ready state.

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[10] Albert's account is aimed at explaining asymmetry and the connection between records and thermodynamics. His focus is not on concerns about everyday use and as such is not designed to answer these questions. This criticism is aimed at the suitability of the account for the present problem and not within the context of Albert's own work.

As a result a stable and identifiable evolution is a precondition for a record. The other condition is being able to identify a specific correlation between some aspect of the actual present state (i.e. the deviation from the expected evolution) and a specific event in the past. If we can only identify that in general the state of the system is not what is expected then this is not highly informative in the way that records tend to be. The deviated state must directly link back to a specific and identifiable event which caused the deviation. Albert's account of this assumes that this is identifiable purely from the evolution of the ready state. However, in more realistic and less idealised systems there could be many interactions which render the final state completely uninformative about any particular interaction. For example a single footprint on a perfectly smooth beach tells us about the person that passed by but a footprint on a beach already trampled and churned into a mess doesn't tell us about anything in particular and would be hard to identify.

Both these conditions can be summarised under the condition that a record is a *robust correlation* (or set of correlations) between the record and some past event. Robustness here can be defined as the ability to withstand noise.

Noise in information theory is classified as unwanted modifications to the signal. Unwanted is interpreted in the context of signalling which comes with a defined goal (to transmit the desired signal). However noise can also be interpreted in a less anthropocentric way by defining it as *irrelevant* contributions to the system.[11] Noise can be seen as irrelevant modifications to a record from other interactions and the internal fluctuations of the system. This noise is inevitable in any system. When the state of the record is retained despite the effects of noise then it is robustly correlated to the past state and the state of the present record can be explained by this correlation.[12] Changes to the past event correspond to changes to the record and contributions from noise can be disregarded because they do not make a defining difference. This also acts to make the correlation identifiable as only one interaction or past event influences the current state of the record to a significant extent. Robustness also makes a record distinguishable despite the natural variation in the expected evolution given slightly different initial conditions (which can be classified as irrelevant noise), removing the need to have a highly specific ready state with which to calculate the expected evolution.

Robustness against noise is part of what a record *is*. Robustness singles out a correlation and transforms it into an informative record (as opposed to Albert account where records exist when we have a ready state and any considerations of noise are an afterthought). This goes back to the distinction between records and retrodiction. While the latter uses the whole present state, the former focuses on just a limited part of it to encode limited information. We must therefore be able to ignore all the other details of the present state (and all details of the system being recorded except the relevant feature which affected the record); the record must be robust against the influence of these details. Without robustness no clear correlation can be identified and we do not have an informative record. Section 5 will explore this in more depth when looking at how records contribute to emergence.

Many factors go into achieving robustness. The first is the use of stable, often macroscopic, systems. Their evolutions will be easily predictable and independent of the microscopic details of the system itself as well as many small interactions with external systems. These microscopic details can be classified as irrelevant noise.

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[11] This mirrors the use of noise in Dennett (1991) where he considers the existence of real and objective patterns which arise in nature. To define these more formally he explains how using a pattern with a certain amount of noise obscuring it can more efficiently describe the state of the system then individually specifying every detail. Additionally the dynamics governing the system can be described more simply and efficiently by disregarding contributions from noise and focusing only on the evolution of the patterns. The patterns are identifiable despite noise partially obscuring them and their existence is independent of whether or not we are able to detect them with our current best apparatuses.

[12] There is a slight nuance here in that in some cases we will consider the correlation between the present record and a past event and in other cases where the actual interaction is less important it might be more useful to consider the correlation between the record system and the recorded system as it presently is. In either case the robustness of that correlation is the same, the latter sense may be more useful for understanding quantum darwinism.

This leads to the conclusion that most records - particularly naturally occurring records - will be macroscopic.

However, microscopic records are possible; especially when a human agent is involved and can deliberately design a system which is robust against noise. This is what happens in fields such as nano and quantum computing. But even in these instances noise can never be completely eliminated and micro systems are very prone to being disturbed by fluctuations or interactions. This leads to the introduction of another important method to ensure robustness: *redundancy*. This technique - commonly used in signalling in error correction coding - creates multiple copies of any individual record so that errors due to noise in one can be corrected by comparison with the copies.[13] Individual micro "records" cannot properly be considered records as there is no way to identify a correlation between the system and a particular past state. The record could be correlated as expected or it could be correlated to a source of noise instead. Creating multiple redundant micro records means that although each individual micro record cannot properly be called a record as it does not give reliable information, taken together the redundancy of the information ensures that a robust correlation holds.[14]

To summarise, this gives us a general account of how records work. They must have a correlation to a past state that is robust against noise. The stability of a system is an important background condition to this but using redundancy is often the necessary condition to make a record informative. The use of redundancy also generalises beyond the technical, microscopic systems in quantum and nano-computing; it can be used to explain records much more generally. For example, consider a footprint in a muddy path. Mud is rarely, if ever, particularly smooth. It is normally created by, for example, the ground being disturbed by many people or animals passing through. An already churned up muddy path is a difficult record to read. It contains many "records" however most will be unidentifiable as anything specific. If an identifiable footprint can be found then it is because we see a shape that has a clear correlation to the shape of a boot which stands out from the general noise of dips and troughs around it. This robustness is important for identifying the record. A partial footprint may still be identifiable but the less of it that remains the harder this becomes. The different parts of the footprint outline form a sort of redundancy.

There are two ways redundancy is working here. First there is a straightforward sense: only a partial footprint is needed for us to be able to identify it. The imprint of the heel, maybe with the pattern from the sole of the shoe, is often enough to make it clear that this is a footprint. The entire footprint therefore contains a redundancy of partial footprints and this redundancy allows for robustness against noise. Even when partially destroyed the record remains informative. One might object to using the term redundancy in this situation. It is not straightforwardly many identical copies of the same information; instead many similar correlations are used. However it is still the case that we have a surplus of information. Each fragment is possibly informative, just as a single micro memory device in quantum or nano-computing can encode information. But it could easily be obscured by noise. Adding many similar records verifies the information in each one and reduces the chances of errors.[15] The second sense of redundancy is less obvious and is required for the individual parts to be informative at all. Each fraction of the outline is correlated to the foot and contains some information about it in virtue of this. But there is a minimal size of fragment that is needed for us to identify the mark as being a footprint at all. What size is somewhat context dependent: an expert tracker needs a smaller fragment than a layperson and some parts of the footprint are more recognisable than others. But below a certain size it is unidentifiable; it is just a random mark in the mud. The fraction itself remains unchanged and it is still correctly correlated to the foot, but no information can be extracted from it. The correlation cannot be separated out from noise. Only by collecting together many similar fractions - a redundancy - to form a larger fragment can a record be formed. The redundancy of insignificant correlations creates a robustness that stands out from the background noise. While a small mark may be the result of anything a distinct line

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[13] In quantum error correction coding this involves using a redundancy of *entangled* qubits so as to avoid the no-cloning theorem.

[14] The word redundancy is often taken to mean eliminable and playing no essential role. The argument here is that the many copies *are* essential. They are redundant in the sense than any single copy is eliminable provided the overall redundant set remains.

[15] Further redundancy can be found when, for example, the footprint is part of a set of footprints one after another.

is much more clearly the result of one thing or another. Another example of this sort of redundancy is pixels in a photograph. Each pixel is correlated to the subject of the photograph but a single pixel can tell us little to nothing. It contains only very minimal information and could easily be effected by noise. But the pixels taken together create a highly informative photographic record. The information that a certain pixel is blue is verified by its placement in a whole set of blue pixels which show us a picture of the sea. While a single black pixel among these blue ones tells us there was probably a speck of dust on the camera.

A certain amount of redundancy is needed for any information to be extracted, and once this minimal level is reached further redundancy helps to protect against errors. All records seem to have this feature. Sometimes it varies as to whether we label the entire redundant set as one record (for example we might say that a footprint is a single record or a photograph is a single record) or whether we count all the many parts individually as records (each pixel in the photograph is a record). This difference is arbitrary and redundancy features regardless. In the former we say the record is a record because it has many redundant parts. In the latter we say the record is a record because it is part of a redundant set; when taken independently of that set it is not informative.

4 Records in Quantum Darwinism

The question remains of how this understanding of records can help us understand why records are useful in generating classical emergence. The initial starting point for applying the general account of records to quantum darwinism is that there is a striking similarity between Zurek's language and the way that records were defined in the previous section. The creation of redundancy in quantum darwinism is what singles out a single correlation (the pointer basis) and makes the individual records informative. As the photon scattering case study showed, an individual photon is not a record unless it is part of a redundant set all decohering the same central atom. This use of redundancy seems the same as the redundancy described in records generally. However what remains to be shown is that this can be connected to the definition of robustness against noise. Noise has not so far featured in the analysis of decoherence presented here so this similarity of using redundancy to identify a correlation needs more careful examination before a comparison can truly be drawn.

Showing this will also serve a dual purpose by setting up a lot of the arguments needed to show that records are related to the screening off condition of emergence which section 5 will draw together in more detail.

4.1 Redundancy and Noise

Care must be taken when connecting decoherence to noise. In the initial quantum superposition of the system (prior to decoherence through interaction with the environment) there are quantum correlations which are phase relations between subsystems of the Hilbert space of the system. These manifest as interference effects. Joos (2000) rightly cautions against any interpretation of these correlations as noise and of the superposition as an ensemble. Doing so would imply that the system is in a definite but unknown state and the quantum correlations are simply obscuring it. But this would not account for the presence of non-local features of superpositions, specifically the presence of interference effects. Noise obscuring an unknown state would not result in these effects.

Only after decoherence has occurred should we consider the analogy with noise. The insistence from Joos (and also Schlosshauer 2019) that decoherence should not be considered in terms of noise largely stems from attempts early in the literature to separate decoherence out from other processes in quantum systems. In particular from dissipation. Dissipation - energy loss from noise processes such as fluctuations and imperfections in the system - can have a similar effect to decoherence in damping the off-diagonal terms of the density matrix. In contrast, decoherence specifically describes the effects of entangling the system with the environment and the loss in information this produces. During the process of decoherence the system becomes correlated (entangled) with the environment and some of the quantum correlations in the system are replaced by the environment-system correlations - this process singles out a pointer basis. The original phase relations from the system superposition are delocalized throughout the total combined system-environment (and eventually throughout the entire universe) (for more detail see Zurek 1982; Joos 2000; Joos & Zeh 1985). The information the quantum correlations hold is spread throughout the entire combined system, while records of the pointer observable are created in many parts of the environment. This corresponds to the off-diagonal terms in the density matrix of the system-apparatus (with the environment traced out) tending towards 0. The state can then be treated as if it was an ensemble of measurement results (although technically it is more complex as the measurement problem - how a single result gets selected - remains unsolved; but this is not relevant to the problem at hand here). Decoherence can be shown to proceed on a different timescale to dissipation.

The association between noise and dissipation comes from the specific usage of noise that is common in that literature, mainly meaning fluctuations. However, the definition of noise given in section 3 is more general and can encompass a wider range of effects. Noise is defined not just as fluctuations and random effects but more generally as irrelevant contributions to the record which may hinder our ability to identify the robust correlation between record and system. This encompasses a wider range of phenomena including systematic low level details which have negligible effect on the overall state of the system and its evolution. Also notably when applying the concept of noise to records this is *after* the environment has become correlated to the system. The process does not *proceed* through the effects of noise. But this does not mean that we cannot apply the generalised concept of noise to the quantum correlations that are delocalized throughout the environment after decoherence.

So the challenge is to show that the quantum correlations (interference terms) are irrelevant and can therefore be classified as noise. This strongly connects the project to accounts of emergence in the philosophical literature. The irrelevance of lower level details is a commonly cited criterion for dynamic emergence. Wallace (2012) and Franklin (2022) both show that the interference terms are irrelevant for the evolution of the resulting classical state. I will not repeat their full analysis here; although it will be discussed further in section 5. What they show is that the system - described by the reduced density matrix with the environment traced out - is effectively diagonalized and obeys classical dynamics and probability calculus. This justifies treating the interference terms as irrelevant.

Much of their analysis is directly applicable here. However there are two issues with carrying it over to justify the irrelevance of the quantum correlations to records. First, quantum darwinism shifts the attention to the environment and no longer traces it out to leave the diagonalized reduced density matrix. The justification of considering the interference terms as irrelevant focused on the system itself and its dynamics, this justification does not necessarily carry over to the environment. Second, the irrelevance to the dynamics does not automatically help us understand the information-theoretic context of records in which the dynamics do not play any major role. Instead it must be shown that the quantum correlations are noise with respect to the measurements the observers make of the environment.

4.2 Local versus Global

We can find our justification by considering the difference between the global and the local environments and how only the latter is relevant to records. When taking the environment as a whole the interference terms delocalized throughout it cannot be ignored or dismissed. Various authors stress this point. Despite the irrelevance of the interference terms to the reduced density matrix of the system the interference terms are still relevant for the joint state of the system-environment. The total joint state remains in a pure superposition. Joos & Zeh (1985) state that "The interference terms still exist, but they are not *there*" (p. 224). By this they mean that the quantum correlations (entanglement relations) found in a superposition state - which the interference terms represent - are not destroyed when a system is entangled with the environment. Instead the correlations are spread throughout the entire system-apparatus-environment combined system. While the reduced density matrix of the system is effectively diagonalized the overall state is not; the interference terms are still present even if they are not in the original system. As such these terms are still highly relevant for the dynamics of the total system. In particular the entire combined state still obeys unitary dynamics and is fully reversible. An operation over the whole environment would allow an observer - at least in theory - to reverse decoherence. Given that the full state of the system-environment retains the superposition Joos (2000) stresses that the interference terms in the reduced system cannot be regarded as irrelevant noise. Additionally, moving away from dynamics and back to the information theoretic framework, a measurement of the whole environment and not just a fraction of it would allow an external observer to observe interference effects as well as gain information about more than just the pointer observable. In the context of quantum darwinism such a global measurement would fail the classical standard as it would disturb the superposition and would not be verifiable by others.[16]

To this last point we can reply with a practical note: such a global measurement may be definable in principle but practically would be very difficult to achieve. It would require the large environment to be perfectly isolated from the observer else the observer would be part of the environment and have to include themselves in the measurement. In many cases we consider the spread of decoherence through the environment to eventually spread throughout the whole universe. Any realistic observer within the universe would be unable to perform measurements at this scale. Even considering a smaller, more limited, environment where a global measurement is more feasible quantum darwinism requires that the information is redundant enough for observers to potentially perform individual measurements on different fragments of the environment. As such a global measurement on the whole environment would have to be on a significantly larger scale than any common place measurement on just a fragment. The in principle possibility of the global measurement does not relate to the practical considerations of how we make observations in the world. The latter was the motivation for quantum darwinism; it aims to explain why we make observations of a classical world all around us. Commonplace observations are made locally on fragments of the environment.

Moreover, despite being *in* the environment, records do not make up the whole of it. In fact, as emphasised by the introduction of redundancy, only a small fragment of it makes a record and this is repeated many times. Meanwhile the relevance of the quantum correlations in the environment - both to the dynamics and to global measurements - requires the *global* combined system. The essence of quantum darwinism is showing that measuring fragments of the environment puts a classical limit on the information that can be extracted (only information about an observable is available). The global superposition state is irrelevant to the local fragment.

The local scale is definitional of classicality. Looking at the notion of classical information, what distinguishes it from quantum information is how parts relate to the whole. In the classical realm knowing a composite system implies knowledge of its parts. This does not hold true for quantum systems where the state of the whole cannot tell us about the parts; the parts do not necessarily have well defined states at all. Measurements on a joint quantum state reveal more information than any sequence of measurements on its component parts. But even for a quantum system local measurements allow us to extract a clearly defined subset of the total information: the classical subset. This is information about observables rather than the

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[16] A measurement could be seen as the observer simply becoming part of the environment itself and entering into the entanglement relations. The point remains the same that a second external observer could not now just measure the environment and corroborate the first observers results. They would also have to include the first observer in their measurement as part of the environment.

state itself. For each individual record making up part of the environment the information it gives is purely about the classical state of the system.

On top of this Zwolak and Zurek (2017) show that many parts of an environment are irrelevant to a local observer's measurement. They are considering a complex environment where many parts of it do *not* become correlated to the system at all (and carry no information about it). They show that the existence of these parts of the environment do not have any appreciable effect on the redundancy of records in the environment and how likely an observer is to intercept at least one. As such they argue these parts of the environment are irrelevant to quantum darwinism.

Based on this the quantum correlations spread throughout the environment can be regarded as noise - in the general sense - with respect to the local records that an observer would measure. The conceptual possibility of a global measurement or operation is not relevant to these local records. The quantum correlations are irrelevant contributions to the final state of the record which is determined by its robust correlation to the system.

This provides justification for claiming that the redundancy of records in quantum darwinism protects the system against noise. This matches both senses of redundancy that were described in the context of the footprint example at the end of section 3. First, redundancy has the effect of making a particular correlation identifiable over and above the many other correlations; this is the active process where the creation of records suppresses the other possible bases in favour of the pointer basis. Due to this process the correlation between the observable and the record becomes identifiable against the background of many quantum correlations delocalized throughout the global system-environment state. The latter can therefore be characterised as noise with respect to the former. This is more active than the classical case as the record creation has an appreciable transformative effect on the system while in the classical case it is often passive (the mud does not transform the shoe stepping in it - in most cases at least). But the overall role of redundancy plays the same role of making information identifiable. Second, further redundancy allows for robustness against disturbance by noise in a much more straightforward sense. Here noise is the negligible contributions to the behaviour of the system made by the delocalized quantum correlations, but it can also be the effects of observers interacting with the records and making measurements, and finally it can also be the more specific meaning of noise as fluctuations. An observer can robustly and consistently extract the classical subset of information about the state from the records and ignore the rest of the environment (and the quantum correlations spread through it) as irrelevant to this information.

5 Records and Emergence

Why records are important in the information-theoretic version of classicality is fairly straightforward: records allow for information about a specific system to be obtained through local measurements and for this information to be shared between many observers. This is necessary to establish an emergent classical reality in addition to the existing standard of instantiating classical dynamics and is in some cases a more stringent standard than diagonalization of the density matrix is, as section 2.1 revealed. What is left to explore is how these two conditions of emergence relate to each other. This ties together various threads that have already arisen in the previous section.

Dynamic emergence has been defined in terms of *conditional irrelevance* (Woodward 2021; Franklin & Robertson 2022). This is not specific to quantum decoherence but applies generally to the emergence of higher level theories and ontologies. Conditional irrelevance explains why it is possible to screen off of lower level details to focus on the instantiation of the higher level theory. To understand it we can first consider its counterpart: unconditional relevance. When accounting for the behaviour of a system, it is clear that the microscopic details which the system is made up of will be relevant to the explanation. As the system evolves in time it successively instantiates a series of microscopic states. Hence these microscopic states are unconditionally relevant to explaining the system's evolution. However this description may be very unwieldy, long winded, or complex. Due to measurement limitations the microstate is likely to be impossible to determine and even if we could the resulting calculation to get from the initial to final state may be practically impossible. This is not what scientific practice attempts to do. Instead we note that many of these microscopic details do not have any significant effect on the overall evolution of the system. We can more effectively describe the system by conditionalizing on certain higher level features or properties. The behaviour of the system can now be explained more simply and efficiently by using them. These features could be instantiated by many different possible microstates, hence the lower level details are being screened off and become *irrelevant* to the dynamics of the system. But only once the higher level features are accounted for; hence *conditionally*.

Franklin (2022) applies this account to the problem of emergent branches (assuming an Everettian interpretation) in quantum mechanics. He argues that the off-diagonal interference terms in a decohered system are conditionally irrelevant to the dynamics of the reduced density matrix.

> "decoherence underwrites the screening off of otherwise relevant details and is, thus, responsible for the screened off states' evolving according to a novel (quasi-)classical dynamics." (Franklin 2022, p. 7)

Screening off, in the form of conditional irrelevance, is essential to emergence. The dynamic account uses dynamical laws to justify it. However records can equally indicate that screening off is justified. By the definition of records put forward they must be robust against various noise effects. These include fluctuations and the effects of multiple interactions. It also includes general low level details which are irrelevant to the dynamics. The definition of noise proposed is in exactly these terms: noise is any irrelevant modifications to the record. That realistic records accessible to observers are local - as discussed in section 4.2 - makes some kind of screening off necessary. The global state must be irrelevant to the local variables that form the record (and its correlation to the past state it is recording) so that the local record is able to give information. Conditioning on the information in the record all these details are irrelevant to determining the state of the system.[17]

The analysis of records started by considering how records differ from retrodiction. Retrodiction gives information by taking the entire state of the system and evolving it backwards under the dynamics. In practice of course this is rarely done in completeness. Instead shortcuts are taken to make the calculations possible such as making models of particular phenomena using idealisations and other approximations, all of which allow us to ignore various irrelevant aspects of the world when making retrodictions and predictions about the phenomena. Much of the literature on emergence is dedicated to showing that these sort of methods lead to emergent theories. Records essentially take the use of such shortcuts to the extreme. They require that a specific feature of a local system is able to give information; all the details of the system outside of this specific feature can be ignored and that the system is not significantly affected by external influences. They need not be taken into account and can be treated as noise when making inferences about how the record is correlated to the aspect of the system it is recording. In essence, these details are screened-off. This is what makes a record a record and separates it from the general process of retrodiction.

The work done in section 4.2. has shown that we can treat the wider state of the system-environment as irrelevant to the the state of the records of the pointer observable that are created in many fragments of the

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[17] We can also see that the connection between records and screening off depends on the selection of specific variables of interest as well as spacial locality. For example the cosmic microwave background radiation spans the entire universe but the record itself is only the thinly spread photons from the big bang and we screen off all the other objects that are emitting photons.

environment. This is directly analogous to the dynamic accounts of emergence from Franklin (2022) that shows that these details are irrelevant to the dynamics. The screening off condition underwrites both the dynamical accounts of emergent classicality and the accessibility to multiple observers through records that defines the information theoretic standard of classicality.

6 Conclusion

Records are indicative of the screening off condition needed for emergence. This screening off condition underwrites both the dynamic account and the information account of the emergence of classicality; showing that they are clearly compatible and that either records or dynamics can be used to justify an emergent classical world. Additionally quantum darwinism can be used to caution against basing the dynamic account on purely the dynamics of the reduced density matrix of the system and the irrelevance of the off-diagonal terms. There are cases where diagonalization occurs but the instantiation of classical dynamics is unstable. So diagonalization is not a sufficient condition for emergent classicality, although it is a necessary one - any emergent system can be described by an effectively diagonalized reduced density matrix. In uncertain cases records are an additional indicator for when screening off can be justified. Meanwhile records are a sufficient condition - an environment in which records form will meet the screening off criteria - but not always necessary. There are also cases where the environment is not well suited to forming records but classicality emerges all the same. Internal noise and other influences may be so great that records are instantly distorted and no information can be extracted from them by observers. But taken together the instantiation of classical dynamics and the presence of records jointly ensure that the familiar classical world emerges in a robust and stable sense.

This goes a long way towards understanding the role of records in quantum darwinism and how it fits into the accounts of emergence developed so far. However there remain a number of other questions that could be raised about both records and quantum darwinism that go outside of the scope of this paper.

This paper has focused on quantum darwinism. However, records also appear in a number of other areas in quantum mechanics. A similar use of records can be found in the consistent histories approach to emergent classicality (Halliwell 1999; Gell-Mann & Hartle 1993). More generally records appear in quantum mechanics as soon as there is an attempt to model an observer as a physical system. For example records appear in Everett's relative state formulation of quantum mechanics (Everett, 1957). To further understand the role that records play in emergent classicality it would be beneficial to extend the analysis presented here more generally to the way records are used in quantum mechanics. Riedel, Zurek and Zwolak (2016) explicitly connect the consistent histories approach to quantum darwinism by showing that the introduction of a *redundancy* of records can solve the set selection problem in which one of the possible consistent sets is selected (analogous to the pointer basis selection problem). In this case we can expect that much of the analysis given here directly holds given the centrality of redundancy. However records were used prior to this with a less explicit reliance on redundancy. Instead the focus is on coarse-graining and noise which is introduced by ignoring all but certain variables (Gell-Mann & Hartle 1993). In particular it is noted that to achieve stable classical dynamics it is necessary to go beyond the minimum coarse-graining required for decoherence and give a coarser-graining with more consideration of noise - this is comparable to how quantum darwinism requires us to go beyond mere diagonalization. The link between records and noise provided here could be beneficial to explain what is happening even in the absence of explicit redundancy and to further explore how coarse graining leads to emergence. This is interesting especially as coarse graining is often looked to for explanations of irreversibility in quantum mechanics and in other areas such as the asymmetry of thermodynamics (e.g. Wallace 2012). The asymmetry of records is also much discussed and has so far been attributed to the past hypothesis (Albert 2000). A connection between records and coarse graining, as well as the irreversibility in quantum decoherence, could help extend our understanding of record asymmetry and how it connects to the thermodynamic asymmetry.

Finally the presentation of quantum darwinism here has largely concerned the particular way that it uses records; this has been used to bridge the difference between the dynamic account and the information account. But although records are central to the theory, they are not all that quantum darwinism has to offer when it comes to defining classicality. The motivations behind quantum darwinism come from asking questions about how measurements and the scientific method connect the quantum world to the classical. What the exact definition of classicality is on these terms has been the subject of some debate. Zurek's original statement was that classicality is objective states where objective means that it can be determined by many independent observers. Brandao, Piani & Horodecki (2015) (among others) additionally emphasise *agreement* among observers and further split the definition into objective observables versus objective outcomes. The latter can be related to the necessity of intersubjective agreement for the scientific method, Adlam (2022) argues that this is an important consideration for the interpretations of quantum mechanics. It is worth asking whether quantum darwinism is just an isolated theory which adds to the dynamic account through its use of records or whether the information approach is valuable for how we think about emergence and classicality more generally. Thinking about the epistemic conditions necessary for the discovery of both the higher level theory and the lower level theory may be as valuable for understanding emergence as looking at the dynamics is and may provide new ways of considering the relationship between levels.

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