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Comparing approaches for carbon dioxide removal

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Greenhouse gas removals—old news repackaged

Alternatively known as greenhouse gas removal (GGR), carbon dioxide removal (CDR), or negative emissions technology (NET), the concept of removing greenhouse gases (GHGs)—primarily CO_2—from the atmosphere has been gaining increasing academic, industrial, financial, and political attention over recent years as corporate and national commitments to net-zero targets proliferate. Practically all pathways to net zero include essential contributions from NET, typically 10%–20% of current national emissions.

However, removing CO_2 from the atmosphere is a much more established concept than one might think. The concepts of bioenergy with carbon capture and storage (BECCS)[1] and CO_2 disposal in carbonate minerals—the precursor to what is today referred to as "enhanced weathering" (EW)—have both been actively discussed since the mid-1990s.[2] Direct air capture (DAC) was proposed from the late 1990s.[3] The potential for including negative emissions as part of an emissions trading scheme (ETS) was first suggested over 20 years ago,[4] but there has been little practical, legislative, or regulatory progress to date.

When these pathways for removing CO_2 from the atmosphere were first proposed, their purpose was to manage atmospheric CO_2 concentrations without needing to limit access to fossil energy. At this time, modern renewable energy was not nearly as developed as it is today. Although Article 2 of the 1992 UN Framework Convention on Climate Change calls for stabilizing GHG concentrations to avoid "dangerous anthropogenic interference" with the climate system, the 1997 Kyoto Protocol focused entirely on emissions rates. Whereas the former implies a transition to net zero at some point, the latter does not.

This paradigm shifted rapidly in the 2000's. In 2008, the UK committed to an 80% reduction in economy-wide remissions—an unprecedented commitment at that time. However, even then the "need" for "at scale" deployment of CDR was unclear. Much of the required mitigation could be achieved via the (relatively) conventional approaches of energy efficiency, fuel switching, increased use of non-fossil energy sources, and carbon capture and storage (CCS). BECCS was included as a theoretical modeling construct as it was deemed the most carbon-efficient use of finite biomass resources, freeing up space to leave difficult emissions elsewhere in the economy. At this time, CDR—mostly in the form of BECCS—had made its way into various integrated assessment models (IAMs), and was not, initially, overly scrutinized. However, as time went on, observations regarding the impracticability of various model outcomes became more common, leading to increased emphasis on alternative

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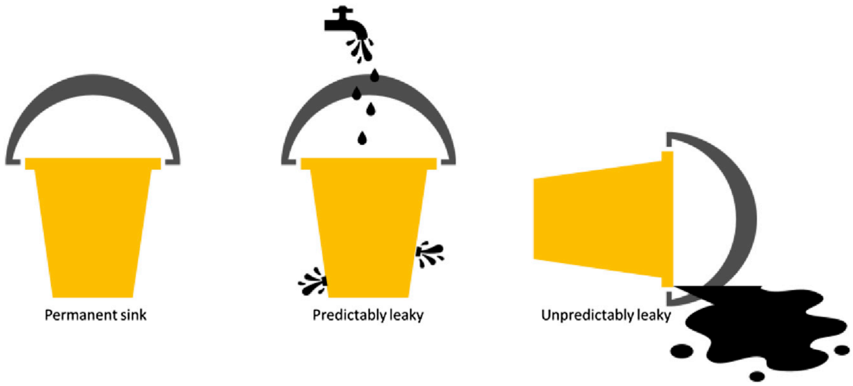

Figure 1. Distinguishing between different classes of carbon sinks on the basis of their "leakiness"

Permanent sinks might include geological sequestration (e.g., BECCS or DACCS) or enhanced weathering; predictably leaky stores might include biochar options.

pathways to the removal of GHGs from the atmosphere.

It was not until the 2015 Paris Agreement, and the subsequent special report by the IPCC on 1.5°C, that the need for the at-scale deployment of CDR was crystalized. To put "at scale" in context, today, total anthropogenic emissions are on the order of 50 $Gt_{CO2,e}$ per year. By 2100, total global CDR is anticipated to be on the order of 10–20 $Gt_{CO2,e}$ per year. In other words, the CO_2 removal industry has the potential to grow to a scale that is comparable to the contemporary fossil fuel industry.

Overflowing interest in CDR

Since about 2019, national and corporate pledges to reduce total CO_2 emissions to net zero by between about 2040 and 2070 have abounded, with the UK, China, and India targeting net zero by 2050, 2060, and 2070, respectively. Over 400 of the top global 2,000 firms have already set voluntary net-zero targets. Where pathways to achieve these goals have been articulated, there has often been substantial reliance on CDR pathways to compensate for "hard to abate" sections of the economy, or for elements of a corporate supply chain over which the corporation with the net-zero pledge had limited or no agency.

This increased focus on CDR has also led to concerns that CDR is, at best, a dangerous distraction from the real task of mitigating emissions (the "moral hazard" argument), or, at worst, a cynical effort to "greenwash" operations and effectively enable business as usual to continue.

Some of this concern appears rooted in an essentially philosophical interpretation of climate goals: is the aim to reduce net CO_2 to zero, while remaining agnostic about technologies and fuels; or is it to "defossilize" the global economy by expeditiously switching entirely to renewable energy sources—primarily wind, solar, and hydro? The desirability of each of these approaches is largely down to personal preference and national policy.

A less contested reason for these concerns is the relatively low price and dubious veracity of much of what is currently available in the offsets market—often referred to as the voluntary carbon market (VCM).[5]

Part of this concern may well arise owing to confusion in taxonomy. There appears to be a persistent conflation of "CO_2 avoided", "CO_2 utilized", and "CO_2 removed". Tanzer and Ramirez[6] set out clear criteria for CDR; in order to deliver CDR, CO_2 must be physically removed from the atmosphere in a manner intended to be permanent.

This statement, while clear, engenders two follow-on questions; namely, what does permanent mean, and how will we know when CO_2 removal has actually taken place, i.e., the monitoring, reporting, and verification (MRV) question?

Can leaky buckets help?

CO_2 is a particularly problematic GHG not, in fact, owing to its global warming potential (GWP), but owing instead to its longevity in the atmosphere—as well as the sheer quantity of its anthropogenic production. It then follows that, in order to avoid climate damage, CO_2 would need to be removed to a store of equivalent duration—but what does this mean?

The value of permanent versus temporary storage was first addressed by Herzog, Caldeira, and Reilly[7] in 2003, and while there is no consensus answer, the available evidence would seem to imply that permanent removal equates to some tens of millennia,[8] if not substantially longer.[9] Though there is currently no widely accepted definition, as a potential "industry best practice", Stripe and the Frontiers initiative are currently stipulating a minimum 90% probability of 100% CO_2 retention at 1,000 years after emplacement.

This is not the say that carbon removed for shorter periods has zero value—indeed, the value proposition of temporary removals could well be a function of when the removal happens; before or after peak warming, for example—but it should not be conflated with permanent removal. Large volumes of low-cost, shorter-duration removals would be valuable, particularly if they coincided with peak warming and, critically, could be demonstrably shown to store CO_2 for shorter periods.

Nor is permanence simply a binary issue. As illustrated in Figure 1, some

Table 1. Illustration of the different permanence and immediacy attributes of different CDR pathways

	Permanent removal	Non-permanent removal
Immediate removal	DAC, BECCS	Biochar, construction timber, utilization as reagent, land use change, soil carbon
Delayed removal	EW, BECCS	Afforestation, biochar, peatland restoration, soil carbon

CDR pathways which deliver non-permanent CO_2 removal are even more complicated.

stores, e.g., geological stores, can deliver permanent storage on a climate-relevant timescale. Others, such as biochar, "leak" in a predictable way.[10] Finally, some non-permanent stores, such as forests, present the potential for catastrophic failure events, e.g., forest fires.

A permanent sink only needs to be filled once. Although a "predictably leaky" sink can be "topped up", this does imply potentially substantial ongoing operating costs for however long the carbon needs to be stored. The "unpredictably leaky" sink presents a different proposition altogether. Specifying the relative value of these three classes of sinks is beyond the scope of this short contribution, but it is clear that they are not equivalent.

Moreover, the services provided by the different CDR pathways vary not only in terms of their permanence, but also in terms of immediacy. For example, direct air carbon capture and storage (DACCS) will lead to the immediate and permanent removal of CO_2 from the atmosphere, whereas EW will lead to the permanent removal of CO_2, but at a relatively slow rate dictated by a combination of factors describing the mineral chemistry and also the ambient conditions. Conversely, afforestation will lead to the non-permanent removal of CO_2 from the atmosphere, and again, relative to normal contractual terms, forests take a substantial period to grow. BECCS has the potential to deliver permanent and immediate carbon removal, but only if the bioenergy resource involved does not incur significant carbon debt associated with direct or indirect land use change (iLUC). Further, owing to the fact that biochar decays with time, this is an inherently non-permanent and leaky store, with similar potential for carbon debt arising from iLUC. This is illustrated in Table 1 below.

Thus, though the permanence of BECCS, DACCS, and EW is clear, and biochar decay is at least somewhat predictable, the integrity of the carbon stock in an afforestation project is exposed to *force majeure* events that can cause premature reversal, e.g., fire, pests, or disease.

In any carbon removal contract, there are two principal parties—the originator of the carbon liability,[11] i.e., the emitter of fossil carbon, and the acceptor of the carbon for storage, e.g., a landowner who is providing an afforestation service. These two parties will need to negotiate over how liability is divided (including whether government plays a role). This is particularly important in the context of international exchange, where governments will be expected to validate storage as successful at some timescale of permanence, so that storage credits can be exchanged internationally under Article 6 of the Paris Agreement.

Importantly, the prospect of repeatedly buying temporary removals for a climate-relevant period is neither desirable from the perspective of the originator, nor credible from a commercial perspective. Simply put, the probability of a given company existing in 100 years to continue addressing their carbon liability is low. Thus, permitting carbon polluters to repair a fraction of the damage they cause, with the public sector subsequently and inevitably addressing this liability, is tantamount to the contemporary subsidy of pollution.

It is therefore evident that the CDR service provided by, and consequently the climate repair value associated with, each of these pathways are far from equivalent.

A tree is not a stone

In the past, DAC has been described as an "artificial tree".[12] Although this analogy is understandable in that both trees and DAC units have the potential to remove CO_2 from the atmosphere, it fails to capture the diversity of environmental services that the various CDR pathways provide.

DAC is a relatively energy-intensive method for removing CO_2 from the atmosphere. BECCS provides a combination of energy services (heat, power, or mobility, as a function of the technology pathway chosen) as well as permanently removing CO_2 from the atmosphere. Afforestation, on the other hand, provides a wide range of environmental services, with carbon removal being only one of many.

This concept is illustrated in Figure 2. It is already commonplace to recognize and quantify the value of the energy services provide by the BECCS pathway, and it will be increasingly important to specify and quantify the discrete value of the other pathways and avoid lumping them all together as "carbon".

The role of MRV in deploying CDR

Fundamentally, the services that CDR pathways provide are either to compensate for residual positive CO_2 emissions to the atmosphere as part of a net-zero strategy, or the net removal of CO_2 from the atmosphere as part of a strategy to transition to net-negative emissions. Either way, the ability to

	CDR Pathway				
Service	AF	BC	EW	BECCS	DACCS
CDR	✓	?	✓	✓	✓
Energy System				✓	
Crop yield enhancement		✓	✓		
Soil enhancement		✓			
Air quality	✓				
Water quality	✓				
Biodiversity	✓				
Ecosystem services	✓				

Figure 2. Non-exhaustive list of environmental services provided by various CDR pathways

unambiguously verify the location and stability of the removed CO_2 is on the critical path to contracting for CO_2 removal.

For some CDR options, MRV protocols have been developed whereas, for others, significant work is still needed. There are two fundamental approaches to MRV. Firstly, direct detection of CO_2 can be used to provide tracking of stored CO_2 through time, e.g., fluid CO_2 injected to geological storage. Secondly, the CO_2 is not directly imaged, but the permanence, or conversely the leakage, is modeled or calculated through time, so that monitoring is more focused on the process of operation, with less ability to measure the outcome. Starting with geological sequestration used for CCS to avoid CO_2 emissions, and BECCS and DAC to remove CO_2 from the atmosphere, MRV protocols are well-developed.[13] CO_2 can be readily metered as it is being injected into the subsurface and, via a variety of approaches, the movement of the injected CO_2 can be reliably tracked as it moves through the geological storage site. In principle, this monitoring could be continued until the CO_2 has been immobilized via one of a number of trapping mechanisms.[14] In practice, this may take a substantial period, ranging from decades to centuries, and it may be more practicable to monitor the CO_2 for the duration of active injection plus a sufficient period post-injection to verify that the CO_2 is behaving as expected.

One key point is that the discussion around geological CO_2 sequestration has progressed from one of "single-CO_2-source-to-single-CO_2-sink" to a CO_2 storage hub model, where CO_2 from multiple sources is mingled in a common transport system and injection to a storage site run by one operator. Thus, as the store operator takes ownership of CO_2 from many originators, it will likely be necessary to further disentangle CO2 sources—be they CCS or CDR projects—from the operation of the CO_2 store. Once a "store closure certificate" has been issued, responsibility for the CO_2 store would revert to the original owner or jurisdiction government.

This is essentially an elaboration of the ideas set out in the 2016 Oxburgh report on CCS,[15] and recognizes that the real environmental service being provided is via the storage of CO_2 leading to CO_2 emissions being either permanently avoided or removed from already emitted atmospheric content.

In the context of enhanced weathering, any CO_2 that reacts with a mineral substrate can be expected to be permanently stored. Broadly, there are two ways of achieving this—bringing CO_2 into contact with minerals containing cations reactive with HCO_3^- in an engineered process as discussed by Kirchofer et al.,[16] or simply by exposing the minerals to the atmosphere and waiting. In the case of the former, MRV is trivial. As the CO_2 reacts with the substrate in a fully controlled environment, a mass balance on the CO_2 or the carbonated material will confirm the reaction. In the case of the latter option, MRV is inherently more complicated, as the material may well be distributed over a large area, and the carbonation reaction will proceed as a function of a number of factors, including ambient temperature, presence of water, soil pH, and so forth. Thus, the rate of atmospheric CO_2 removal will vary with time, and the reactions will proceed at a different rate as a function of time and location. This is a good example of the second type of storage—where the process is essential to follow and verify because the CO_2 stored cannot be directly detected by MRV.

Consider biochar—assuming that the biomass has been sourced as sustainably as possible such that there is no carbon debtto repay, the quantity of CO_2 removed is greatest when the biochar is first applied to the soil. Thereafter, the char begins to decay such that after a period of decades to centuries, there may be very little left. Moreover, depending on soil type, the application of biochar to soils can have a methanogenic effect via the "priming" of microbial activity as a function of a range of factors, including soil pH and the presence of water, etc.[17]

Understanding the overall contribution of a non-permanent carbon sink to climate change mitigation is highly complex and depends not only on the rate of storage reversal, i.e., leakage, but also on when this reversal occurs, and on the background rate of anthropogenic warming at the time of reversal. For example, if the reversal effectively shifts carbon emissions forward in time to a date on or before emissions and warming peaks at a global level, then the net impact of the CDR activity would actually be to exacerbate climate change.

In principle, ongoing MRV of a variety of CO_2 sinks is possible, with protocols varying with each CDR pathway. In the context of *ex situ* enhanced weathering, for example, this could involve sampling land to ascertain mineral content. Given that this is something that landowners already can do in order to optimize land management, this MRV requirement would merely represent an intensification of an existing activity. Suitable commercial laboratory facilities exist, and though the capacity would likely need to be significantly increased, there is a base from which to build. However, it must be recognized that establishing a reliable reference point for the carbon content of the land would be a non-trivial exercise.

In practice, however, this is likely to be costly and may well be perceived as onerous by many landowners. Further, although landowners may well be interested in the land productivity improvements associated with incorporating biochar or mineral spreading, such benefits will need to be weighed against the costs of assuming long-term MRV responsibilities required to claim any CDR payments, or indeed the liability for stored carbon which might leak. If landowners find that costs outweigh the benefits then it might make sense for this MRV responsibility (and financial upside) to sit with others, such as the providers of the biochar or enhanced weathering material.

A framework to deploy non-permanent CDR pathways

So, what to do?

In principle, one could elect to store CO_2 in non-permanent sinks, with the commitment to either transfer an equivalent amount of CO_2 to a permanent sink once they become more affordable at a later date, or to simply repeatedly renew the non-permanent sink as it "expires," until such time as the impact of the original CO_2 emission has been fully compensated for.

However, as discussed earlier, this may be quite challenging to achieve, and, in practice, these commitments may prove exceptionally challenging to enforce or verify that they have, in fact, been met. Importantly, this would imply a very substantial inter-generational commitment, with no evidence of this having previously occurred.

Moreover, there is a much more mundane challenge. Given the timescales involved and the relatively short lifetimes of many firms, what happens if, for entirely unrelated reasons, the holder of the carbon liability ceases to exist? In principle, this could be mitigated via the permanent transfer of liability with the initial transaction. However, this simply cascades liability, requiring the invention of new means to verify the re-removal of an equivalent to the original quantity of CO_2 in the future. At a minimum, this seems a cumbersome and potentially costly approach. At worst, it is prohibitively complex and un-enforceable.

Identifying a feasible and practicable solution to this question is becoming urgent owing to the many pressures to begin to monetize all manner of CDR through voluntary carbon markets, and even extending to proposals for incorporating CDR into the UK and EU ETS.

An alternative could be simply to recognize that, just as not all GHGs have an equivalent GWP, not all GHG removal pathways (CDRs) have an equivalent climate repair value (CRV).

For example, if 1,000 years were to be taken as a proxy for "permanent", once the CO_2 has been confirmed as stored in a geological sink, there can be a high degree of confidence that this CO_2 store will persist for several millennia, if not substantially longer. Thus, CO_2 stored in this way could reasonably be assigned a CRV of 1, and thereafter, non-permanent CDR pathways could be allocated a CRV of less than unity.

This provides an inherently simple approach that would have both the effects of readily enabling the incorporation of CDR into an ETS and creating the means to incentivize the most efficient CDR pathways and minimize carbon leakage across CDR value chains.

This approach would also have the impact of "right pricing" CDR relative to mitigation, such that concerns regarding mitigation deterrence should be thoroughly addressed. For example, Microsoft recently paid an average of \$20/t for predominantly "nature-based" removals.[18] Although there are relatively few forms of mitigation options that are, *ceteris paribus*, cost competitive with \$20/t offsets, once an appropriate CRV is accounted for and MRV is priced in, almost all forms of mitigation would become more cost-effective.

Thus, those who have committed to net-zero targets, both corporations and nations, would be able to concurrently avoid accusations of greenwashing, and ensure prudent disbursement of taxpayers' money.

Importantly, different countries will have varying capability for removing and storing CO_2—comparative advantage is inevitable, as is the international trade in the necessary components and feedstock. Some regions are better endowed with geological CO_2 sequestration capacity, others will have abundant rocks or soils with geochemical alkalinity required for enhanced weathering, whereas in other contexts there will be an abundant supply of sustainable biomass, and so forth.

It is therefore vital to ensure the viability of the international trade in GHG removal services. This will be a non-trivial exercise. Individual countries will inevitably seek to privilege their own natural biogeophysical advantages, but the reward is likely to be worth the effort since it could lead to a robust set of market institutions.

Finally, there might be reasons for excluding certain categories of CDR, at least initially, because of the nature of the market. An even bigger

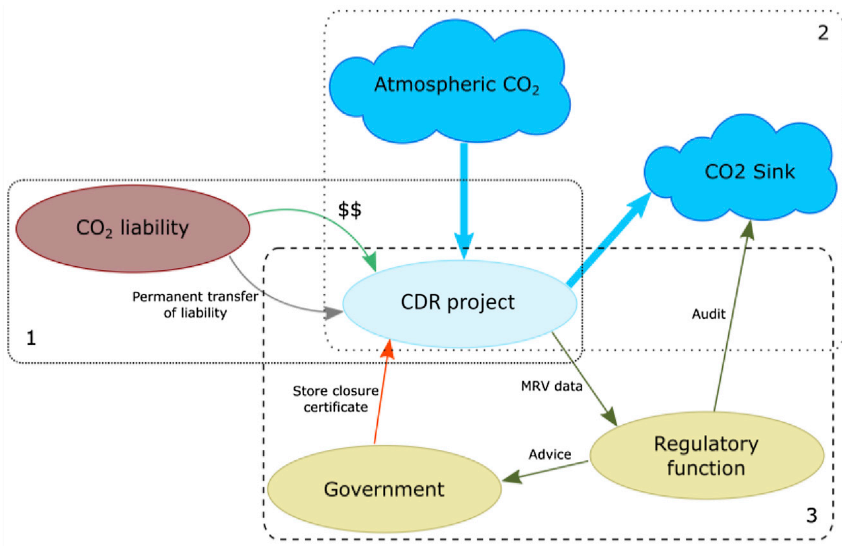

Figure 3. Schematic of carbon liability value chain

challenge for some forms of non-permanent storage is not just leakage from the local store (whether slow or abrupt), but more systemic effects. Afforesting a tract of land and perfectly preserving that forest with state-of-art MRV does not in any way guarantee that the entire forest area can be counted toward climate repair. Because there are national and international markets for timber, one hectare preserved may simply mean the equivalent hectare (or a large fraction thereof) will be logged elsewhere. This could argue for focusing first on certain types of non-permanent storage, such as biochar and soil carbon sequestration, that would not suffer from this potential cannibalization of effort seen in forests for example.

Delivering CDR projects in practice

Building on the foregoing discussion, a possible value chain for the transfer of carbon liability is illustrated in Figure 3. This should focus the mass balance on the atmosphere, and not be distracted by local incumbent accounting rules. As can be observed, there are three distinct dimensions to a carbon removal project. The first is when the original carbon liability is permanently transferred to the CDR project developer. The word permanent is important here as, regardless of what happens to this carbon subsequently, the originator of the carbon emission is unlikely to be willing to accept any further responsibility in the future.

In the second dimension, the carbon is removed from the atmosphere and transferred to a sink. The extent to which phases one and two will be in series or in parallel remains to be seen. As the market matures, it is likely that the carbon removal will have to already have taken place, but in the near term, *ex ante* transactions appear to be possible to at least some extent.

A third dimension will be the interaction of the CDR project with an independent third-party verification process and/or regulatory oversight, whereby the CDR project can be audited, and the integrity of the CO_2 store confirmed. The concurrent and efficient interaction of the regulatory function with the relevant government will be key for both national and corporate accounting purposes, and for the completion of the project. Once the carbon is deemed to be permanently removed and behaving in a predictable manner, the project can be completed and liability for the store could revert to the state. For most non-permanent stores, this end-state would never be reached and so MRV would need to continue on a rolling basis, and if monitoring ever ceased then the store would no longer be considered to be contributing to GHG removal.

Thus, a given CDR purchase could combine a number of CDR pathways to deliver a cost-effective portfolio which will reliably and verifiably compensate for the original carbon liability.

Conclusion and recommendations

So, what comes next?

It seems as though CDR is here to stay, and all signs point to this industry growing rapidly over the coming decade. However, concerns regarding its role in efforts to meet climate targets persist. In this contribution, a framework has been set out to transition to credible GHG removal.

Although this will not be straightforward, it is anticipated that the payoff will be worth the effort. Without a rigorous effort to increase the credibility of CDR pathways via effective MRV, there is a very real possibility that although there will be many projects, ultimately the market will never scale up, which is entirely justifiable. From here, we can see five key next steps in this discussion:

1. Establish an internationally consistent definition of permanence that should be used across all CDR options.
2. Develop a workable framework for the definition of the CRV for individual CDR pathways.
3. Develop an internationally agreed-upon approach for calculating the carbon removal efficiency of a given CDR project, noting that the supply chains may well be transnational.
4. Agree on a methodology to incorporate CDR in existing ETS, noting that many ETS may well

need to be modified to become net-zero compliant.

5. Establish a mechanism for the international trade of CDR, within the provisions of existing ETSs, or simply against a given country's carbon account, sufficient to be certified for inclusion in the nationally determined contribution (NDC) submitted to the UN Framework Convention on Climate Change.

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AUTHOR CONTRIBUTIONS

N.M.D. conceived and led the writing. D.M.R. and S.H. contributed to the ideation, writing and editing.

DECLARATION OF INTERESTS

N.M.D. is a member of *Joule's* Advisory Board. All authors consult widely for a range of international public and private organizations involved in carbon management.

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