Focus Article

Climate change tipping points: origins, precursors, and debates

Chris Russill*

The article reviews the origins, precursors, and main proponents of climate change tipping points, and the debates that the tipping point concept has occasioned. The importance of dynamical systems theory, GAIA theory, and abrupt climate change to the main proponents of tipping point warning systems is noted and situated in historical context. The ‘semantic confusion’ that animates contemporary debates, it is suggested, results not simply from a narrow conception of tipping points, but from inattention to the way metaphor was used to reshape climate policy. A deeper understanding of dynamical systems theory and its origins (both mathematical and metaphorical) is recommended for addressing the value of tipping points in policy.

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INTRODUCTION

The origins of climate change tipping points—as a metaphor, as a concept, and as a way of envisioning the earth—are numerous and difficult to trace in all their complexity.

The short story involves the emergence of abrupt climate change as a ‘new paradigm’. In 2002, a National Academy of Sciences (NAS) report argued that the paradigm had been ‘well established by research over the last decade,’ yet it was ‘little known and scarcely appreciated in the wider community of natural and social scientists and policy-makers’.[1] The notion of climate change tipping points emerges in this context to mediate scientific and policy concerns by using a popular metaphor. Indeed, authoritative claimsmakers, such as Richard B. Alley, the chair of the NAS committee on abrupt change, John Schellnhuber, and James Hansen all spoke of tipping points in a colloquial, nonformalized way around 2004–2005 in arguing that the policy framework for climate change developed through the UN FCCC did not properly encompass such threats. On this ‘short story’ account, a previously unrecognized body of knowledge acquired policy significance through an authoritative scientific synthesis that gained public recognition through a culturally resonant frame.

The long story is more complicated and reflects the concept’s close connections to ecology and dynamical systems theory. In the 1970s, a mathematical branch of ecology was developed in terms of dynamical systems theory to address stability, complexity, and chaos in environmental systems, especially in the work of Robert May and C. S. Holling. Holling, in particular, sought an integrated perspective on the science, policy, and management of ecological resilience using the concepts and methods of dynamical systems in collaboration with William C. Clark. Resilience, a popular concept today,[2] is typically thought to concern how systems respond and recover after perturbation. In the work of Holling, Clark, and others, resilience also involves the idea of multiple equilbria (or alternative stable states) and the role of perturbation or disturbances in switching a system into a different state (or failing to do so).

In the early 1980s, the ecological systems approach was extended to considerations of global climate change while Holling and Clark were at the International Institute for Applied Systems Analysis (IIASA). The opportunity to influence ‘the CO_2 question,’ as it was then called, was afforded by Thomas Schelling, a dynamic systems theorist, whose contribution to the 1983 NAS report, *Changing Climate*, argued that the development of energy policy required

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*Correspondence to: chris_russill@carleton.ca

School of Journalism and Communication, Carleton University, Ottawa, ON, Canada

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social science (particularly economics).[3,4] Schelling was influenced in his advice to US policymakers by the modeling done at IIASA, which Holling directed at the time, and Clark adapted Schelling's approach to reframe 'the CO_2 question,' using the ecological modeling approach developed at IIASA.

Clark developed the IIASA approach into a policy proposal that was presented to the 1985 Villach Conference (the event often credited with establishing the direction of the IPCC). Clark's (1985) proposal agreed with Schelling that the physical science underpinning political concern with CO_2 emissions was not sufficient for evaluating the range of societal responses that governmental policies could encourage.[5] In Clark's view, policy on the CO_2 question should be recast 'as a problem of risk assessment and risk management,' and dynamic systems approaches could permit scientists to better inform and manage a wide range of anticipated threats. In particular, it was necessary to incorporate the abrupt and catastrophic changes suggested by atmospheric scientists (Reid Bryson, Stephen Schneider) and oceanographers (Maurice Ewing, Wallace Broecker). 'The time is ripe for the 'extreme event' element of the carbon dioxide debate to tap this emerging understanding' (Ref 5, p. 36, 41). By reenvisioning abrupt change through dynamical systems theory, and by modeling how stability is contingent on cascading effects derived from slight variations, one could learn to manage the risks of complex systems like the climate.

The Clark proposal failed to influence how science informed policy on CO_2 and climate change. Climate change tipping points, in this respect, are a return of the repressed, as the metaphor emphasizes threats posed by extreme events (or what the IPCC describes as large-scale discontinuities). In fact, the first use of tipping point in the context of climate change was John Schellnhuber's informal suggestion to a British journalist that the large-scale discontinuities discussed in the IPCC AR3 were tipping points.[6] Yet, the metaphor was used subsequently to encompass much more, and developed in the context of Gaia theory to advance a conception of climate change policy grounded in risk assessment and dynamical systems theory.

In this article, I situate the context, origins, likely precursors, and main proponents of climate change tipping points with respect to dynamical systems theorists. If we accept the 'short story,' as I have called it, tipping points are a concept that refashions climate policy as risk management using the conceptual tools and mathematical techniques of dynamical systems theory. In the 'long story,' the metaphorical quality of tipping points is more evident, and tipping points inscribe a new attitude toward risk into science and policy by mixing technical discourse and popular connotations to scale ecological models of environmental complexity to the entire planet.

HISTORICAL CONTEXT

Dynamical systems theory and its many variants (chaos theory, complexity theory, catastrophe theory, criticality analysis, etc.) intersect with climate change science in diverse ways. In one popular account, the origins of chaos and complexity science are identified with Jean-Baptiste Joseph Fourier's law of heat propagation and the science of thermodynamics (Ref 7, pp. 104–106). Fourier, of course, is often credited with identifying the greenhouse effect. If one looks beyond mathematical formalizations, the origins of dynamical systems thinking are also found in literary efforts to grapple with environmental changes precipitated by the 19th century industrialization of Britain.[8] On Heidi Scott's account, models sensitive to how slight variations compound to affect environmental stability emerge first in the narratives and metaphors of literary writers before receiving conceptual development in ecological science. Metaphor and narrative, Scott argues, are not simply prior to science, but also an alternative means of 'modeling ecological change,' (Ref 8, p. 4) and this raises interesting questions about the different roles of metaphor and mathematical formalization in modeling earth systems, especially if the role of analogical reasoning is properly identified.

In the earth sciences, as well as intellectual culture more broadly, the atmospheric modeling of Edward Lorenz is the usual point of reference for discussions of dynamical systems theory. Lorenz played a central role in the 1965 conference, 'Causes of Climate Change,' which Spencer Weart describes as a 'turning point' in the development of 'a novel and foreboding way of looking at the future of climate' (Ref 9, p. 39). In this conceptualization of climate, the earth was viewed as 'a complex system, precariously balanced,' and it 'showed a dangerous potential for dramatic change, on its own or under human technological intervention, and quicker than anyone had supposed' (Ref 9, p. 40).

In Weart's history, the conception of climate change as complex, abrupt, and characterized by flipping, switching, or tipping is a recurrent fascination of scientists since the mid 1960s, one with diverse sources and influences, yet indebted significantly to the mathematical modeling approach Lorenz contributed in his opening address to the conference. Dynamical systems modeling of atmospheric change would proliferate in the 1970s and 1980s, particularly in the work of

Gregoire Nicolis and his colleagues.[10] As the IPCC AR3 acknowledged in discussing Lorenz's work, 'the study of nonlinear dynamical systems has become important for a wide range of scientific disciplines, and the corresponding mathematical developments are essential to interdisciplinary studies' (Ref 11, p. 113).

The tipping point metaphor, however, originates in another branch of dynamical systems theory: Thomas Schelling's modeling of neighborhood 'tipping' in the late 1960s and early 1970s, which he used to explain patterns of racial segregation in US cities, a body of work inspiring Malcolm Gladwell's popularization of the tipping point concept.[12] In Schelling's work on neighborhood tipping, as well as Gladwell's popular adaptation, this is no mention of climate change, and tipping points refer to human behavior.

Why did ecologists influenced by Thomas Schelling first use concepts from dynamical systems theory to integrate abrupt and catastrophic climate change into a policy framework in the mid 1980s? Why did Lorenz's work not lead directly to such proposals? While the answer likely involves the 'basic research' conception of atmospheric science in the mid 1960s, as well as the separate tracks pursued by atmospheric modeling and oceanography,[13] it was Clark's (1985) view that one needed first to inscribe a new attitude toward risk into climate policy: 'For most environmental questions where scientific uncertainty is important, the policy analysis community has come to view its task as one of risk assessment and management. For the carbon dioxide question, the policy analysis community, almost without exception, ignored the uncertainties and their implications altogether' (Ref 5, p. 36). If climate change policy is understood as a risk assessment, and if the distinctive threats posed by abrupt changes gain increasing cultural salience, then an approach to scientific modeling able to encompass such risks should gain increasing traction in policy development.

As I document below, climate change tipping points were initiated as a simple metaphor for characterizing the distinctive threats posed by abrupt change, yet the metaphor quickly fed back into scientific and policy developments, much as Katherine Hayles and Brandon Larson find metaphors working in information theory and sustainability science respectively. A 'feedback' metaphor, according to Larson, engenders 'a circular feedback between our view of ourselves and our view of nature' (Ref 14, p. 18). Tipping point works in this way because of the interplay between its popular connotations and history of technical usage, and it was the cultural salience generated by Gladwell's work that led to warnings of climate change tipping points.

FIRST USES

In 2005, the primary research on climate change tipping points was a single article: Lindsay and Zhang's claim to have identified a tipping point for Arctic summer sea-ice.[15] Yet, there were informal references to tipping points from climate scientists in 2004–2005. Richard B. Alley used the phrase to sensitize people to the dynamics of abrupt change,[16] and John Schellnhuber was quoted by journalists at the BBC and The Guardian warning of 12 potential tipping points in the earth system.[17,18] In 2005, Schellnhuber popularized his 'Tipping Points Map' and co-organized a workshop on the topic with Tim Lenton and others.[19] Jon Foley, in 'Tipping Points in the Tundra,' used the phrase to title his synthesis of research on Arctic sea-ice.[20] Each of these uses was colloquial and metaphorical.

In December 2005, at the American Geophysical Union (AGU), James Hansen put the term into wide circulation with a clear and urgent warning of climate change danger: 'we are on the precipice of climate system tipping points beyond which there is no redemption' (Ref 21, p.8). The warning was widely reproduced and suggested an imminent threat. Tipping points were the point of no return and they recast climate change as abrupt, nonlinear, irreversible, and dangerous to humans and other species in the near term. Hansen's use of tipping point was metaphorical, like his references to time bomb, slippery slope, or Achilles heel.

Hansen's warning was the result of his own synthesis of evolving science—an effort to connect the dots from diverse fields of inquiry in ways the IPCC had not. It also had an ongoing catastrophe as its immediate context. The disasters precipitated by Hurricane Katrina were widely perceived as a failure of the US government to heed warnings of impeding danger from government scientists. As well, FEMA official, Michael Brown, described the catastrophe as the result of crossed tipping points.[22] The science had been clear but the emergency management system failed to respond to insistent warnings. It was in this context that Hansen circulated an unequivocal warning of climate change danger using the tipping point metaphor—messages that were amplified considerably in 2006 by news coverage and Al Gore's filmic treatment of the failed efforts of NASA officials and the US government to censor Hansen's warnings of tipping point danger.

By mid-2006, journalists noted a tipping point trend in news media,[23] and *Nature* editorialized to scientists on the appropriateness of the terminology (the editors suggested tipping points were best used to describe societal dynamics rather than the climate system).[24] Yet, the published science on climate change tipping points was still meager in 2006.[25] The few scientific papers using the terminology were studying the dynamics of Arctic summer sea ice melting and this proved a popular example in the ensuing news coverage of tipping points.[26]

The debate on tipping points has tended to involve concern over ‘alarmism,’ or the idea that an apocalyptic imaginary had taken hold of climate discourse, and ‘fatalism,’ the idea that fearful messages would generate disengagement or apathy (Ref 25, p. 336). Proponents of the tipping point concept addressed such concerns by emphasizing the importance of a risk management framework for climate policy. Possibility, not likelihood, should figure more prominently in planning, and abrupt changes were not manageable in the same way that gradual change would be. It remained unclear what was entailed by such advocacy for risk management, other than greater attention to the possibility of discontinuous forms of systems change.

In 2007, Tim Lenton and John Schellnhuber, two scientists known for their contributions to Gaia theory, called for an ambitious reconfiguration of climate policy around the threat of tipping points.[27] Tipping points, in this conception, were not simply a metaphor conveying urgency, but a scientific concept and geophysical phenomena.

The proposal was strikingly bold. Climate policy, in their view, was transformed into a problem of risk management by the threats and uncertainty associated with tipping points. In fact, Lenton and Schellnhuber recommended the elimination of approaches that failed to encompass tipping points: ‘climate protection strategies that clearly do not avert the risk of reaching a tipping point can be excluded from policy decisions’.[27] In addition, they called for a ‘Third Industrial Revolution’ to be precipitated by a ‘socioeconomic tipping event,’[27] on the assumption that tipping points for societal dynamics could be identified and controlled, a conceit encouraged in Malcolm Gladwell’s popularization of the concept.[28] Oddly, the negative connotations of geophysical tipping points, as events to be avoided, were joined to a positive valuation of socioeconomic tipping points, as events to be precipitated intentionally.

In ‘Tipping Elements in the Earth’s Climate System,’ Lenton, Schellnhuber, and their colleagues supported their policy proposals with a scientific synthesis that defined tipping points, formalized their conditions (‘tipping elements’), and proposed an early warning system for their detection.[29] It is important to situate their conception of tipping points with respect to its conceptual precursors and the policy window opened by renewed attention to abrupt climate change in the early 2000s. In brief, I suggest the tipping point concept reanimates Clark’s (1985) proposal, an idea made plausible by Clark’s handling of the ‘Tipping Elements in the Earth’s Climate System’ manuscript for PNAS (as a managing editor for the journal), and his previous collaborations with John Schellnhuber.

PRECURSORS

> one may speculate as to which other Gaia-type metaphors may be ‘activated’ (Ref 30, p. 18)

Hansen’s warning and those by Lenton and Schellnhuber reflected the new salience of abrupt climate change science in the 21st century. Abrupt climate change often involves scenarios of North Atlantic thermohaline circulation (THC) shutdown—a dimension of meridional overturning that was proposed in the 1980s, modeled using dynamical systems tools in the 1990s, and then nominated as a ‘grand challenge’ in the 2002 NAS report publicizing the new paradigm (Ref 1, p. 106) (after which it figured prominently in popular culture due to the interest of Hollywood, the Pentagon, Gore’s An Inconvenient Truth, and much besides).

THC shutdown is important to our understanding of tipping points in two respects.

First, THC was developed conceptually in terms of switching—switches, mode switching, and switch points—and these notions are clear precursors to tipping points. In its iconic depiction, THC was imagined in terms of an oceanic conveyor belt, one having on/off modes. The conveyor belt metaphor was inspired by—and would help popularize—the science of ‘Dansgaard–Oeschger events,’ (D/O events) which were discovered in 1960s ice-core data.[31] D/O events are rapid transitions in the earth’s climate before the relatively stable Holocene era of the last 10,000 years. D/O events suggest our current climate is but one possible mode of operation. The climate has switched abruptly in the past and may do so again.

D/O events were connected to North Atlantic THC shutdown by Wallace Broecker. In brief, Broecker proposed that the conveyor belt was the switch or trigger for the abrupt climate changes represented by D/O events,[32]—a switch he would label the ‘Achilles heel’ of the climate system.[33] Broecker would subsequently link the phenomena to global warming by suggesting that Greenland’s deteriorating ice sheet could trigger THC shutdown, which might in turn switch the global climate system.

Second, THC shutdown and abrupt climate change were taken up by dynamic systems theorists.

By his own account, John Schellnhuber is the pivotal figure in developing the notion of climate change tipping points, and he claims with some justification that he 'introduced the overall tipping-points concept into the scientific community dealing with climate change around the year 2000, through a 2001 Linacre lecture in Oxford, co-authored by Hermann Held'.[34] While their paper does not discuss tipping points as such, Schellnhuber and Held develop the idea of choke points and switch points in ways that are suggestive of their later conceptualization of tipping elements and tipping points (notably, the language of switch points disappears with the introduction of tipping point terminology). It is interesting to note that Schellnhuber and Held hope to activate 'other Gaia-type metaphors,' a comment recognizing the importance of metaphor (Ref 30, p. 18). Broecker, of course, had piled metaphor upon metaphor in speaking of a 'conveyor belt' as an 'Achilles heel'.

In their paper, Schellnhuber and Held transform Gaia theory into earth system analysis using dynamic systems theory. 'Earth System science can draw from an ever richer pool of disciplinary tools, not only from the traditional Earth sciences, but also from systems theory and non-linear dynamics' (Ref 30, p. 16). Lenton, at this time, is also developing complexity theory to rework Gaia theory.[35]

While noting the initial contributions of Gregoire Nicolis, Schellnhuber and Held propose a different method to reconceptualize THC and D/O events in terms of dynamical systems theory. The fuller relationship of dynamical systems theorists to Broecker's work is beyond the scope of this article. However, in the 1990s, Stefan Rahmstorf brings together THC and dynamical systems modeling, and Schellnhuber and Held expand on his work to suggest that many aspects of climate change, particularly THC shutdown and D/O events, are best understood using dynamical systems theory. The conceptual language Schellnhuber and Held develop for their analysis are choke points and switch points. As mentioned above, this terminology is nearly synonymous with the tipping elements and tipping points used by Lenton and Schellnhuber later in the decade. The goal is to integrate the earth sciences using dynamical systems tools in order to develop 'control parameters' for understanding critical thresholds that have switching or tipping points. On the basis of this understanding, humanity could manage climate change threats, if not the earth system more broadly.

In 2005, Clark, Schellnhuber, and Paul Crutzen would call for a 'new paradigm,' one bringing together Schellnhuber's claims for 'earth system analysis' and Crutzen's identification of 'the anthropocene'.[36] The goal was to identify 'critical elements' that worked like 'control knobs' in the earth system (Ref 36, p. 8). The 'critical elements' were generated through a 'criticality analysis' (dynamical systems theory) and represented graphically on a global map as choke points and switch points (Ref 36, p. 10). Schellnhuber would re-title and publicize this map as a 'tipping point map'. Tipping point was the 'Gaia-type metaphor' Schellnhuber and Held had speculated upon in their initial paper, and the popularity of Broecker's 'conveyor belt' metaphor was their heuristic for the efficacy of metaphor.

ARCTIC SEA-ICE DEBATES

Arctic sea-ice figures prominently in tipping point debates. In 2005, Lindsay and Zhang[15] reported a tipping point for summer sea-ice in the Arctic, a claim initiating a brief discussion of tipping points in the models informing IPCC assessments.[37,38] By 2006, tipping points were featured prominently in news reporting of climate change, often with reference to North Atlantic THC shutdown and Arctic sea-ice.[23–25]

In recent years, as concerns with THC shutdown have receded, the effort to identify Arctic sea-ice tipping points has intensified. In 2007, the IPCC AR4 offered no hint of sea-ice tipping points despite inclusion of Lindsay and Zhang's research. IPCC assessment reports lag ongoing research, yet Richard A. Kerr, the longtime journalist covering climate change for Science, reported on ensuing developments in Arctic sea-ice modeling and concluded, 'there are no tipping points' (Ref 39, p. 1655) Mark Serreze, an Arctic sea-ice specialist, warned frequently of a tipping point in 2006–2007. Yet, Serreze (2011) stepped back from his previous claims: 'the tipping point argument can perhaps be laid to rest' (Ref 40, p. 48). The Arctic summer sea-ice would disappear, probably soon, and this was a serious concern. It did not have a tipping point though. The same conclusion was restated and affirmed in the IPCC AR5 (Ref 41, p. 1079).

These reassessments frustrated scientists advocating for tipping point warning systems. As concerns with THC shutdown have receded, the emblematic example of climate change tipping points has shifted to the Arctic. Arctic sea ice, as an immediate and visible concern, helps prove the value of tipping points as a scientific concept as well as their significance for policy concerns. An acknowledgment that tipping points were absent would indicate overreaching if not undue alarmism, a charge that scientists are usually keen to avoid. In this respect, Arctic sea-ice has acquired a broader symbolic value, important on its own terms, but also now a key site for deciding the importance of tipping point diagnostics more generally. If the ice has a tipping point, the warning systems advocated by dynamical systems theorists are needed to understand the nature of the transitions and the potential for intervention; if it does not have a tipping point, their policy proposals are of more limited scope and relevance than first suggested.

In 2012, Lenton and his colleagues approached the matter by arguing that the debate over tipping points was 'semantic,' a dispute occasioned by loose definitions of terminology.[26] The problem, in their view, is the popular association of tipping points with 'bifurcation points' and 'irreversible change' (Ref 26, p. 60). By conflating irreversibility with tipping points, the potential reversibility of the melting of summer sea-ice in the Arctic was taken as evidence that tipping points were absent. If, however, one recognizes that tipping points are reversible, the debate should dissipate. In this way, the debate was described as 'semantic confusion,' and media attention to the debate was charged with distracting attention from dangers of tipping points: 'we should stop debating the existence of tipping points and start managing the reality of dangerous climate change in the Arctic' (Ref 26, p. 61).

The charge of 'semantic confusion' returns us to the question of incorporating popular metaphors into scientific terminology. While one might presume the confusion lies in lazy approaches to definition among some scientists and journalists, it is a frequent result when using metaphor to switch the implicit heuristics governing our understanding of environmental change. In this respect, it is useful to see tipping point as a 'feedback metaphor,' which Brendon Larson describes as, 'scientific metaphors that harbor social values and circulate back into society to bolster those very values' (Ref 14, p. 22). Citing Evelyn Fox Kellner, Larson affirms that, 'The use of a term with established colloquial meaning in a technical context permits the simultaneous transfer and denial of its colloquial connotations … The colloquial connotations lead plausibly to one set of inferences and close off others, while the technical meaning stands ready to disclaim responsibility if challenged' (Kellner cited in Ref 14, p. 15). The colloquial connotations of tipping points lend the technical meanings broader relevance and give them purchase in a range of policy and cultural fora that mathematical formalizations cannot enter in unmediated fashion; yet, this relevance 'may simultaneously imbue its associated cultural values with new authenticity,' and this encourages a broader range of experiences and cultural perspectives to coproduce its subsequent meaning (Ref 14, p. 15).

In this respect, the confusion over tipping points is not semantic, at least not in the simple sense of mistaken definition, but the result of adopting metaphors that are culturally resonant, and that are intended to shift popular heuristics for environmental change. These heuristics are elicited by metaphor and used to bring scientific inquiry and cultural values into diverse points of contact.[42] The continual slippage of the referent, as the invocation of tipping point oscillates from geophysical phenomena to societal dynamics, is indicative of generative or feedback metaphors, and is another source of semantic confusion worth addressing in a more expansive way.

CONCLUSION

Climate change tipping points inscribed a new attitude toward risk into scientific and policy discourse. Tipping points, in this respect, transformed an implicit heuristic for understanding environmental change into an overt metaphor, and the metaphor increased the cultural salience of risks that are difficult to handle using conventional forms of climate modeling and probabilistically oriented risk analyses.

Tipping points involve both metaphor and mathematical formalization, both cultural connotations and precise technical meanings, and the semantic confusion that has accompanied their wider use could be traced back to the competing visions of ecological change that accompanied 19th century industrialization.[8] The importance of dynamical systems theory to their technical meaning should not be understated, however, even as the metaphorical origins of climate change tipping points are often suppressed in such theories, and this negative attitude toward metaphor limits our understanding of the semantic confusion that results from mapping popular terminology onto new fields of reference.

Whether it is James Gleick's *Chaos*, Mitchell Waldrop's *Complexity*, Al Gore's *Earth in the Balance*, Malcolm Gladwell's *The Tipping Point*, Maarten Scheffer's *Critical Transitions in Nature and Society*, or James Lovelock's numerous publications on Gaia, all popular accounts of dynamical systems intended for the nonexpert audience emphasize its nonintuitive and surprising worldview. In this respect, a more sophisticated vocabulary for understanding how metaphor and 'frame reflection' organize worldviews is worth developing,[25,42] especially as the proposal for a 'new paradigm' (Ref 1, p. 1), 'scientific revolution,'[27] or 'industrial revolution,'[27] predicated on tipping points is likely to generate conflict. The ubiquity of analogy and metaphor in climate change science offers clear opportunities for understanding the relationship of science and policy in terms of social learning, which could displace the competitive dynamics of shifting paradigms or promoting revolution with more reflexive perspectives on the relationship of science and societal processes.[25]

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