Special Issue

Decision Errors and Accidents: Applying Naturalistic Decision Making to Accident Investigations

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When faced with dynamic and often ill-structured situations, experienced decision makers can quickly recognize and respond to the situations they encounter, a process referred to as naturalistic decision making. Naturalistic decision-making research has addressed decision-making errors in complex systems, including those that have resulted in accidents, and explained the decision making that led to the errors. Although much research has been suggested by accident investigations, little has been written about how accident investigators apply naturalistic decision-making research to decision-making errors in the accidents they investigate. The purpose of this paper is to illustrate the contribution of naturalistic decision making to accident investigation by describing how investigators explicated decision making in an accident that lacked much of the data that investigators and researchers have typically depended on to examine errors and determine accident causation.

Keywords: accident analysis, naturalistic decision making, errors, recognition primed ground transportation, aviation, human error

On November 14, 1970, a McDonnell-Douglas DC-9-31 crashed while on approach to Huntington, West Virginia, killing all 75 passengers and crew onboard. The flight had been chartered by Marshall University to return its football team, coaches, and others to the university from a game in North Carolina. Investigators determined (National Transportation Safety Board, 1972) that the probable cause of the accident was the pilots'

> descent below Minimum Descent Altitude during a nonprecision approach under adverse operating conditions, without visual contact with the runway environment. The Board has been unable to determine the reason for this descent, although the two most likely explanations are (a) improper [pilot] use of cockpit instrumentation data or (b) an altimetry system error. (p. 36)

Over 30 years later, investigators examined the 2003 capsizing of a charter fishing vessel in which 10 of the 17 passengers and the captain were killed. They determined that the probable cause of this accident was "the decision of the master [i.e., captain] to attempt to cross Tillamook Bay bar despite the hazardous sea state that existed at the time" (National Transportation Safety Board, 2005, p. 56).

Cockpit voice recorder data showed the DC-9-31 pilots discussing the prevailing weather and the visibility. Investigators addressed the pilots' deviation from the airline's approach and landing procedures but not their decision to continue descending beyond the minimum descent altitude. By contrast, the marine accident investigators focused on the captain's decision making. Even though both accidents involved crew decision errors made in uncertain, dynamic conditions, errors that directly led to accidents, the marine investigators examined decision making, but the aviation investigators did not. This paper attempts to explain how investigators were able

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to assess the marine captain's cognitive performance despite the lack of recorded data, whereas the aviation accident investigators, who had available both recorded crew conversations and considerable other electronic data, did not. I argue that naturalistic decision making (NDM) research and situation awareness theory, developed in the interval between the two accidents, provided investigators the ability to examine critical operator decision making in accident investigations and to explain how decision errors in the accidents developed.

NDM

At the time of the aviation accident, researchers largely viewed decision making from what has been referred to as a classical (Cannon-Bowers, Salas, & Pruitt, 1996) or a behavioral decision-making (Lipshitz, Klein, Orasanu, & Salas, 2001) model. This model, applied primarily to relatively static settings, when, for example, someone is considering undertaking a major purchase, is applicable to situations in which a decision maker can weigh costs and benefits and where poor outcomes do not directly threaten him or her other than from the consequence of high costs (Johnston, Driskell, & Salas, 1997). However, the model has little applicability to the dynamic and often rapidly changing environments in which transportation accidents occur.

The downing of a civilian Iranian Airbus A-300 in July 1988 by U.S. Navy personnel, after they mistook it for a descending F-14 fighter while they were using a sophisticated tracking system (Department of Defense, 1988), led to research into decision making in dynamic situations (Kahneman & Klein, 2009). Such research, examining decision making in real-world or "naturalistic" environments (Orasanu & Connolly, 1993), focused on settings such as battlefields or complex systems (Kahneman & Klein, 2009) in which decision makers face ill-structured situations; shifting, ill-defined, or competing goals; time pressures; and potentially severe consequences of "poor" decisions (Orasanu & Connolly, 1993). Rather than evaluate alternatives, decision makers in naturalistic environments respond to the circumstances they encounter, a process referred to as recognition-primed decision making (e.g., Klein, 1993a; Klein, Calderwood, & Clinton-Cirocco, 2010). The ability of decision makers to recognize the nature of the particular situations they encounter affects the quality of the decisions they make.

The influence of NDM research on contemporary theory has been considerable. As Klein (2015) observed, "NDM research has changed many core beliefs that used to be held in the basic research and the applied communities" (p. 383). This change in beliefs has also resulted in a better understanding of decision making in dynamic settings by battlefield commanders, airline pilots, and firefighters, among others, thereby assisting those seeking to reduce the likelihood of decision-making errors in dynamic situations.

Decision-Making Errors

NDM research has shed considerable light on cognitive activity associated with decision-making errors. Klein (1993b), for example, defining errors as decisions that the decision maker subsequently recognized as erroneous or would make differently in the future, found that decision errors resulted primarily from insufficient decision maker experience, insufficient information, or incomplete or inadequate mental simulation.

Lipshitz (1997), defining decision errors as "deviations from some standard decision process that increases the likelihood of bad outcomes" (p. 152), applied systems approaches of Rasmussen (1983) and Reason (1990, 1997) to decision errors. He described the "standard procedure" used to establish that a bad outcome resulted from a decision error, tracing backward from the outcome until its root cause is determined, as is carried out, he noted, in accident investigations.

Orasanu, Dismukes, and Fischer (1993) suggested that air transport pilot decision errors developed from either their diagnosis of a situation—that is, their situation assessment—or their response to the situations encountered. Using National Transportation Safety Board accident investigation reports and simulated flight scenarios, they attributed decision errors largely to human information-processing limitations in response to ambiguous or changing cues.

Endsley (1997) suggested that "human errors that are attributed to poor decision making actually involve problems with the SA [situation awareness] portion of the decision-making process as opposed to the choice or action portion of the process" (pp. 269–270). Endsley (1995) described three hierarchical levels of situation awareness. In the first, individuals perceive elements of the current situation; in the second, they comprehend or make sense of those elements; and in the third, they project to the near term their understanding of the current situation. Accurate situation awareness is the first and arguably most critical step in NDM and therefore in effective decision making (Orasanu & Fischer, 1997). Breakdowns at any situation awareness level can lead to inaccurate situation assessment and to decision errors.

Errors from situation awareness breakdowns can be seen in controlled flight into terrain (CFIT) accidents, such as the 1991 crash of an Airbus A-310 near Katmandu, Nepal (His Majesty's Government of Nepal, 1993), and the 1995 crash of a Boeing 757 near Cali, Colombia (Aeronautica Civil of the Government of Colombia, 1996). Investigators' descriptions of both accidents, but not their analyses, demonstrated that the pilots, despite knowing that they were near mountains, lost situation awareness regarding their positions and hence their proximity to the terrain.

Orasanu and Martin (1998) and Orasanu, Martin, and Davison (2001), using data from a National Transportation Safety Board study of pilot errors in commercial aircraft accidents, identified 51 "tactical decision errors," of which 19 involved pilots failing to discontinue an approach in poor weather or continuing an approach that had become unstabilized, errors they characterized as "plan continuation errors." These errors, they argued, illustrate a not uncommon phenomenon of decision makers continuing with a course of action in dynamic circumstances despite the availability of information suggesting that a different course of action is warranted. Among the explanations they offered for this type of error was previous experience. Repeated successful encounters with risky situations, they suggested, enhance decision makers' expectations of success when encountering similar circumstances. Further, altering a decision that has already been made, they observed, requires the decision maker to expend additional cognitive effort to recognize that (a) the situation has changed since the initial decision was made and (b) a different course of action is needed. As Orasanu and Martin (1998) explained:

> Clearly, more cognitive effort is needed to revise one's understanding of a situation or to consider a new course of action than sticking with the original plan whose details have already been worked out. Given that pilots, like most people, are "cognitive misers," they tend to avoid such changes. (p. 9)

Rhoda and Pawlak (1999), studying commercial flights during thunderstorms, found that pilots were more likely to fly into thunderstorms, weather that creates substantial risk to flight safety, when following similar aircraft than when not. The actions of comparably trained operators, using similar equipment, were shown to influence the decision making of those subsequently encountering similar situations.

Helsloot and Groenendaal (2011), using a laboratory-type study, examined decision making among criminal investigators who work, they explained, in environments that "can also be characterized by uncertainty (contradictory or ambiguous information), time pressure (e.g., high work load and performance indicators), and high stakes (determining the outcome of a criminal lawsuit and handling media pressure)" (p. 890). They divided investigators into two groups that received different amounts of information at different rates and asked the groups to allocate the resources needed to address the simulated criminal cases, based on the forensic evidence the researchers provided. The investigators, who often worked on multiple cases, devoted more resources to "emotionally-charged" cases than to more routine ones. Further, when under time pressure, the more experienced investigators allocated resources based on their experience or their first impression of the evidence. The researchers showed that criminal investigators have greater independence in decision making than do those in environments with strict operating procedures. However, the absence of consequences as potentially severe as those transportation system operators may face limits the generalizability of the findings.

Although Helsloot and Groenendaal (2011) applied NDM to the work of investigators, and researchers have studied decision-making errors in transportation accidents, few have described how investigators examine decision-making errors that led to accidents, work that has often provided the material for research into decision making. Considering the contribution of accident investigations to NDM research and the application of NDM to the study of decision errors, there is a need to describe how accident investigators have applied the findings of NDM research. I discuss the investigation of a marine accident to illustrate how investigators applied NDM research to an accident in which no recorded electronic vehicle data were available but where the research enabled investigators to explicate critical decision making nonetheless.

THE ACCIDENT

On June 14, 2003, the fishing vessel Taki-Tooo capsized after its captain crossed the bar at Tillamook Bay Inlet, Oregon, for an intended day-long fishing trip. A bar is an area between an ocean and an inland waterway in which sand, silt, and soil have been deposited. Oceanic forces at these locations, with the relatively low sea depth, can create considerable wave action, potentially endangering vessel crossings. After departing the marina about 0600 (local time), the Taki-Tooo captain transited to the bar, arriving there about 0645, where he waited for favorable seas; the sea state at the bar was particularly rough at the time. At 0715, the captain attempted to cross the bar into the Pacific, but the vessel encountered a large wave and capsized.

Although recorded communications and electronic data were unavailable, other data, such as weather information, bar condition observations, the captain's previous experience, and survivor reports, allowed investigators to examine the captain's decision making and explain his error. Investigators examined the following:

- research on decision making in dynamic situations,
- personal factors that may have influenced the captain's decision,
- weather and bar information the captain obtained, and
- the context in which he made the decision.

Because relevant research on NDM has already been addressed, NDM research will be referenced as it pertains to the specific features of this accident.

Personal Factors

The 66-year-old captain had operated charter fishing vessels in that area for over 26 years. He and his wife had owned the company that owned the Taki-Tooo and the vessel that crossed the bar immediately before he attempted to do so, selling the company about 2 years before the accident. Under the terms of the sale, the captain, who had regularly served as captain on the two vessels, agreed to continue to do so on the Taki-Tooo upon passenger request. As investigators noted (National Transportation Safety Board, 2005), "he was highly regarded by his former customers and they would frequently request that he serve as the vessel operator when they booked a fishing voyage" (p. 12).

Although fatigue has been found to adversely affect decision making (Lyznicki, Doege, Davis, & Williams, 1998; Wilson, Salas, Priest, & Andrews, 2007), investigators ruled it out as a factor after examining the captain's sleep/wake history. Similarly, his medical condition and medication use were excluded as factors after examining the evidence, a routine investigative focus regardless of an accident's circumstances. Finally, recognizing that the captain was to be paid for the charter only if he completed it, investigators considered whether he made the critical decision for financial reasons. They found no evidence that financial factors influenced his decision.

Weather Information the Captain Obtained

The widow of the captain told investigators that both the night before and the morning of the accident he listened to marine weather forecasts and obtained weather information through his home computer. In addition, when serving as vessel captain, he was said to regularly monitor the marine weather while driving to the marina. Consequently, investigators determined that at the time of the accident the captain was cognizant of the wind and sea conditions at the bar and, with his experience, understood the risk they presented to an attempted bar crossing in the Taki-Tooo.

Although the number of the captain's previous bar crossings was not documented (the Coast Guard did not require such documentation), given the number of times the bar had been closed to recreational vessels, at least 1,000 times in 5 years, and the captain's years of operating experience, it was believed likely that that he had encountered similar conditions on multiple occasions.

Why the Captain Decided to Cross the Bar

Leaving the marina, although not imprudent, influenced the subsequent decision making of this and the other captains who transited to the bar. In the approximate 30 minutes that he waited at the bar, four charter fishing vessels also remained there while the captains waited for conditions to improve. Investigators described the various influences on the decision making of those captains:

> While the decision to leave the dock to assess conditions at the bar might have been prudent, it also probably subtly influenced the masters' subsequent decisions to cross the bar rather than return to the dock. By loading passengers on the vessel and taking them almost as far as the bar, the masters' decision-making ability to return to the dock without crossing the bar was diminished. To return to the dock would have meant that each master would have had to personally face and explain his decision to the passengers who had prepared for the expedition and boarded the vessel and whose anticipation for the fishing voyage no doubt had increased as they neared the bar. (National Transportation Safety Board, 2005, p. 43)

Investigators suggested that the captain's assessment of the likelihood of a successful bar crossing while waiting at the bar was influenced by the actions of those captains waiting with him. The first vessel to cross the bar, one that was larger and had more powerful engines than the Taki-Tooo, crossed it about 0650. Investigators recognized that vessel and engine size affect the stability of a vessel; the larger the vessel and more powerful its engine(s), the better it can traverse rough seas. The next vessel to cross was the largest of those at the bar and thus could most effectively cross it. Although the report notes that vessel crewmembers broadcast on the marine radio the hazards they encountered during the crossings, the report does not state whether this information was provided to the captains of those vessels still at the bar.

The next vessel crossed about 0700. The captain had owned and operated it for the company that he had and his wife later sold. It had the same length and had an engine that was about the same size as that of the Taki-Tooo. After that vessel crossed, the Taki-Tooo captain attempted to do so as well and the accident occurred. Investigators described the possible influence of that vessel's crossing on the captain's decision:

> Certainly, he was familiar with the D & D [the vessel that crossed before the Taki-Tooo] a … vessel like the Taki-Tooo but with a slightly less powerful engine. Possibly, the decision of the Taki-Tooo master to attempt to cross the bar a few minutes later was influenced by the successful transit of the D & D. (National Transportation Safety Board, 2005, p. 45)

ACCIDENT ANALYSIS AND DISCUSSION

Although investigators cited only one NDM study (Klein, 1999), the influence of NDM research as well research into situation awareness on investigators' analysis of the accident are evident. The investigators described the situation the captain encountered and noted several of the situational factors that Orasanu and Connolly (1993) described, such as high stakes from severe consequences of a "wrong" decision, shifting or competing goals (e.g., safety in returning to the marina vs. passenger satisfaction in crossing the bar), and most important, uncertainty in the dynamic sea state.

The report addressed the captain's situation awareness regarding the sea state and described his efforts to obtain weather and sea state information the night before, the morning of, and the moments immediately preceding the accident. For example, investigators wrote that while waiting at the bar the captain "continued to monitor the bar conditions, noting the movements of other vessels and the success of their masters' attempts to cross and listening to the radio transmissions from the vessel masters" (National Transportation Safety Board, 2005, p. 45). Although not explicitly addressing situation awareness theory (e.g., Endsley, 1995), the influence of the research on the account of the captain's active search for information to gain Level I and II situation awareness, beginning the night before and continuing to moments preceding the accident when he waited at the bar to observe the conditions, is apparent. Investigators' subsequent comment that "no master can be assured that the conditions encountered when crossing [a bar] will be the same conditions as those observed when the decision to cross is made" (National Transportation Safety Board, 2005, p. 46) addresses Level III situation awareness, projecting system state to the near term. It suggests that even with an accurate understanding of the current conditions the captain would likely not have been able to predict near-term conditions, thus increasing the likelihood of a decision error that affected the safety of the vessel and the lives of those on it.

The report's discussion of the effects of the captain's leaving the dock with the group that had charted the vessel also reflects the influence of NDM research. The passengers' familiarity with the captain meant that he recognized that they would have been disappointed had he remained at or returned to the marina. As investigators described, his awareness of the group:

> would most likely have subtly affected his decision not only to leave port but also to subsequently cross the bar. He would have been motivated not to disappoint those passengers who had traveled some distance to engage in a fishing expedition under his command. (National Transportation Safety Board, 2005, pp. 42–43)

This explanation, although not attributed to researchers, is consistent with that of Klein (1999), and of decision errors Orasanu and Connolly (1993) and Orasanu and Fischer (1997) addressed.

In addition to investigators' characterization of the captain's history of successful bar crossings and their influence on his decision making, "his confidence in his ability to cross [the bar] successfully, accrued over many years, may have led him to minimize the hazards he faced" (National Transportation Safety Board, 2005, p. 46), is consistent with Orasanu and Martin's (1998) explanation of plan continuation errors. As they wrote:

> If somewhat similar risky situations have been encountered in the past and the crew has successfully taken a particular course of action, they will expect also to succeed this time with the same CoA (course of action) e.g. landing at airports where conditions frequently are bad, for example in Alaska. Given the uncertainty of outcomes, in many cases they will be correct, but not always. (p. 103)

Finally, investigators summed their evidence for the captain's decision-making error, describing the facts that led him to decide to cross, in a manner consistent with NDM research findings. The captain did not evaluate the cost and benefits of the alternatives but rather responded to the circumstances he observed, based on his experience. As investigators wrote, his decision:

> was probably influenced by a host of factors, including the request of the passengers for his services, his observations of sea conditions comparable to those he had seen before, his previous experience making the bar transit with this vessel, and his observation of the crossings of the other vessels before him. (National Transportation Safety Board, 2005, p. 46)

Accident Investigation and NDM

In the interval between the West Virginia aviation and the Taki-Tooo accidents, research into decision making has provided investigators the skills needed to better understand operator decision errors in the dynamic systems in which they are engaged, advancing both theory and the quality of accident investigations. Because this research and often critical data were not available at the time of the West Virginia accident, investigators largely focused on operator action errors, without explaining them or examining the decisions that may have led to those actions (Coury, Ellingstad, & Kolly, 2010). In the interval, research has been conducted that has enabled investigators to routinely address such potential influences on decision errors as fatigue (e.g., Jackson et al., 2013; Lim, & Dinges, 2010; Wickens, Hutchins, Laux, & Sebok, 2015), team factors (e.g., Salas, Cooke, & Rosen, 2008; Salas, Grossman, Hughes, & Coultas, 2015; Wilson et al., 2007), maintenance factors (e.g., Antonovsky, Pollock, & Straker, 2014; Hobbs & Reason, 2003; Hobbs & Williamson, 2002), and automation (e.g., Parasuraman & Wickens, 2008; Sarter & Woods, 1995), among others. Similarly, advances in medical research and in pharmacology have improved our understanding of medical antecedents to error in ways not possible four decades ago (e.g., Evers, Rüschenschmidt, Frese, Rahmann, & Husstedt, 2003; Teran-Santos, Jimenez-Gomez, Cordero-Guevara, & Cooperative Group Burgos-Santander, 1999).

Investigators do not apply empirical logic to their analyses and do not subject their conclusions to the hypothesis testing called for in empirical research (Strauch, 2015). They use legal logic of the preponderance of evidence, not inferential statistics, to answer counterfactual questions that can explain error causation and the role of error in an accident. For example, would the operator have committed this error had these factors not preceded it (Australian Transport Safety Bureau, 2007)?

In the Taki-Tooo accident investigation, NDM theory was used to explain the nature of the captain's error; it met the counterfactual analytical requirements of accident investigations. Investigators cited situational factors such as high stakes from severe consequences of a "wrong" decision, shifting or competing goals (e.g., safety in returning to the marina vs. passenger satisfaction in crossing the bar), and most important, uncertain conditions, in this instance the dynamic sea state, which have been identified as characteristics of NDM environments (Orasanu & Connolly, 1993) to explain the circumstances of the error. The evidence for the application of NDM to account for the captain's decision was unambiguous, and as important, no other viable explanation such as fatigue, financial need, medical condition, medication use, cognitive deficiency, or operational factor such as training, experience, or skill level could be identified to better explain his decision-making error. Through the application of NDM, accident investigators were able to meet the requirements of investigative logic better than available alternatives, reconstruct the captain's decision process retroactively, and explain the nature of and reason for the critical decision error that he committed.

CONCLUSIONS

It can be reasonably assumed that contemporary investigators of the West Virginia accident, with the foundation of NDM theory, would address the crew's decision to continue to execute the approach beyond the minimum descent altitude. Regardless of the circumstances, contemporary investigators would be expected to examine this error. They would also likely interview fellow pilots and training pilots to learn about pilots' previous performance and obtain electronic data, such as air traffic control radar data that, to the extent possible, could allow them to understand the background to the error or errors that led to the accident. If available, they would also obtain information from anonymous pilot reporting systems to learn of pilot concerns with the airport and the aircraft. With this information, they could more fully examine the pilots' decision to land the airplane and the context in which they made that decision. By contrast, it is unlikely that an investigation of the Taki-Tooo accident 40 years ago would have addressed the captain's actions, beyond the vessel's bar crossing. With the lack of research on NDM and little understanding of situation awareness, it is difficult to envision how investigators would have examined his decision other than to fault it.

A contemporary approach into examining errors in an aviation accident can be seen in the investigation of a 2001 accident that shared some characteristics with that of the West Virginia one.

An MD-82, an advanced version of the aircraft involved in that accident, crashed in Little Rock, Arkansas, while the pilots were attempting to land during a thunderstorm (National Transportation Safety Board, 2002). Investigators cited several factors that influenced the crew's decision making, including an extended weather-related takeoff delay and a dispatcher's message sent in flight to the crew. "The dispatcher," investigators wrote, "suggested that the flight crew expedite the arrival to beat the thunderstorms if possible, and the flight crew acknowledged this message" (National Transportation Safety Board, 2002, p. 2). Investigators cited Orasanu et al.'s (2001) work to suggest why the crew decided to land despite the adverse weather. As they wrote:

> The NASA researchers found that the most common decision errors occurred when the flight crew decided to "continue with the original plan of action in the face of cues that suggested changing the course of action." The study stated that cues that signal a problem are not always clear and that a decision-maker's situation assessment may not keep pace with conditions that deteriorate gradually. (National Transportation Safety Board, 2002, p. 96)

Today, accidents such as the West Virginia one are, fortunately, rare. Most air transport aircraft today are considerably more sophisticated than was the DC-9-31 operated in that accident, displaying more accurate and more readily interpretable navigation information than was provided on that aircraft. In addition, designers, regulators, and operating companies have applied accident investigation lessons to system operations to enhance safety.

Despite their differences, both accidents illustrate a characteristic decision-making error in which operators in dynamic situations are unable to recognize that their situation awareness—that is, their projection of system status into the near future—has become inaccurate. Accident investigations have shown that when situations are sufficiently dynamic, and when unexpected situations arise, decision makers in "the heat of battle" may exert such a high level of cognitive effort to both diagnose the situation encountered (or acquire situation awareness) while simultaneously striving to safely operate the system that insufficient resources are available to enable them to recognize that their situation awareness is no longer accurate. For example, in the cockpit voice recorder transcripts of pilot conversations in the two CFIT accidents described previously (Aeronautica Civil of the Government of Colombia, 1996; His Majesty's Government of Nepal, 1993), neither pilot team recognized, until it was too late to avoid the accidents, that their flight paths were taking them toward mountainous terrain. Interpreting investigators' findings in both instances illustrates that, despite the pilots' uncertainty regarding their positions, they devoted considerable efforts to understanding the nature of their navigational difficulties while continuing to execute their respective approaches to landing.

Accidents have occurred when operators failed to recognize that their understanding of the situation they encountered had become invalid. Little research into this phenomenon has been conducted. Additional research can, it is hoped, shed further light on the circumstances in which operators who have lost situation awareness fail to recognize that they have done so when making critical decisions. Research may also, it is hoped, add to our understanding of what has been referred to as plan continuation errors. Such research may also explain why operators are more likely to enter hazardous situations while following operators facing similar circumstances, a critical decision-making error that the Taki-Tooo captain committed.

The work of accident investigations and NDM research is, to a large extent, symbiotic. Each relies upon the other to advance its respective field, and the resultant endeavors have enriched both. NDM research, based largely on efforts to explain decision-making errors in events such as accidents, has engendered a literature that accident investigators have applied when appropriate. As this paper demonstrates, the converse is true as well. The findings of accident investigations have been applied to NDM research, resulting in enhanced scope and application of the research. With additional research even greater improvements in understanding and mitigating opportunities for decision errors in accident scenarios can hopefully be developed and implemented.

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