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On the Primitives of Causality: from the Semantics of Agonist and Antagonist to Models of Accident Causation and System Safety

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On primitives of causality: from the semantics of agonist and antagonist to models of accident causation and system safety

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ABSTRACT: Controversial discussions on causality have been present in ancient philosophy since the days of Aristotle. Despite the use of this concept in numerous subjects, there is no consensus on the definition of causality and its possible mathematization. Many authors have analyzed the relation between causes and effects; the predominant school of thought reduces causation to a physical relation (either deterministic or probabilistic) between two events. The distinction between causes and consequences is not always clear and meaningful as different "layers of understanding" may be applied to the notion of causality. From this point of view the cause-effect implication relation can be thought of as a first level representation of causation. By "double-clicking" the link between events, the in-depth layers of causality surface, allowing a better comprehension and distinction of the causality nature. It is then important to understand how causality can be incorporated in an accident model. Several accident models have been recently employed to interpret different contributing factors to an adverse event and to help improve our chances on accident prevention. However, accident models do not focus on the nature of the causal relationship. The causal relationship is always limited to "cause(s) imply effect(s)", but it is never analyzed as to understand the mechanism that lead to such implication. Our language in itself is limited in the ways of describing causal relationships. We will see how the application of the effective metaphor of Agonist and Antagonist actions from the Force Dynamics framework will help analyzing the roles of different actors along the chain of causation. The use of this metaphor, enhanced by the introduction of the Inverse Agonist concept, will provide new insights on the interactions among those actors and will yield the insightful idea of primitives of causality. These primitives will be primal and fundamental notions at the base of a more general concept of causation. We illustrate the use of primitives of causality through an accident example, and we highlight the absence of relevant antagonist and inverse agonist actions that failed to block and de-escalate the accident sequence respectively. We argue that the primitives of causality here introduced allow a deeper understanding of causal mechanisms involved in system accidents and provide a richer basis for conceiving and articulating accident prevention strategies.

1 INTRODUCTION ON CAUSALITY IN ACCIDENT MODELS

> *"We often think, naively, that missing data are the primary impediments to intellectual progress; just find the right facts and all problems will dissipate. But barriers are often deeper and more abstract in thought. We must have access to the right metaphor, not only to the requisite information. Revolutionary thinkers are not, primarily, gatherers of facts, but weavers of new intellectual structures."*
>
> *From "The flamingos smile", S. J. Gould*

Metaphors are prevalent in our language, and it is often arduous to convey abstract ideas without using them. A metaphor (literally a *transport* from the greek verb $\mu\epsilon\tau\alpha\phi\epsilon\rho\omega$) allows the interchange of structures of thought and logic among different domains of the human knowledge. The explanation of new theoretical concepts takes great advantage from the use of already established patterns. A notable example is Rutherford's atom planetary model based on a metaphor with the solar system. Metaphors are quite common also in accident causation models and system safety in general; the use of simplified approaches to reality reduces the complexity and multitude of events, conditions and actors. These models provide a key to interpret many of the different contributing factors of an adverse event and help improve our chances on accident prevention. They are often employed to understand the chains of causality that led to the specific unwanted event.

Table 1 provides a summary of the metaphors recently employed in accident models, following the classification by Lehto & Salvendy (1991). No claim of exhaustiveness can be made and many other classifications are available, as those developed by Laflamme (1990), Kjellén (2000), and Hollnagel (2002). The metaphors employed by each model are presented together with their main features and references for further details. It is important to understand how causality is incorporated in the models of Table 1. Even if they differ by purpose, focus and approach, they all attempt to represent both the phenomenology and the etiology of an accident. The "how?" and "why?" are analyzed and discussed as a series (or a network) of contributory causes.

Combinations of the presented models are also possible. However, neither of the analyzed models focuses on the *nature* of the causal relationship. In other words, whether the sequence of events is viewed as a chain over time or as a network of causes, none of the presented models takes into account the different specifities of causality. The causal relationship is always limited to "cause(s) imply effect(s)", but it is never analyzed as to understand the mechanism that lead to such implication. Our language in itself is limited in the ways of describing causal relationships: a lighted match in a wood or a broken barrier in the defense-in-depth line will, in the same way, be causes that imply the subsequent events/effects. Nevertheless, there is a sharp distinction in the role played by "a match setting fire" or "a failed barrier". Intuition helps us in understanding the underlying distinction for these simple cases, but formal considerations are needed for more complex scenarios. But why is it important to distinguish the "role" of a cause? The answer to this question is the primary scope of this paper. We will see how the application of the simple metaphor of Agonist and Antagonist actions from the Force Dynamics framework will help analyzing the roles of different actors along the chain of causation. The use of this metaphor, enhanced by the introduction of the Inverse Agonist concept, will provide new insights on the interactions among those actors and will yield the insightful idea of "primitives of causality" originally introduced by Talmy (2000). These primitives will be primal and original ideas at the base of a more general concept of causation. The understanding of the primitives of causality involved in an accident may improve our knowledge on the mechanisms that failed to prevent an accident. The introduced concepts will allow us to express risk escalation and de-escalation, and trajectory modification along the risk state trajectory of the system.

The remainder of this paper is organized as follows. Section 2 provides a brief introduction to the concept of causality and the nature of the causal relation. Section 3 presents the metaphor of Agonist, Antagonist and Inverse Agonist and introduces the primitives of causality. Section 4 applies the presented concepts to analyze two of the safety systems involved in the Piper Alpha explosion in 1988. Section 5 concludes this work.

2 THE NATURE OF THE CAUSAL RELATION

Controversial discussions on causality have been present in ancient philosophy since the days of Aristotle. This topic remains a staple in contemporary philosophy and has played a central role in both metaphysics and theology. Nowadays, causality is still a key concept in different fields, such as sciences and ethics (Salmon 1998). Causality is a fundamental notion also in accident prevention and safety; Rasmussen et al. (1990) maintained that "the very nature of causal explanation shapes the analysis of accidents".

Despite the use of this concept in numerous subjects, there is no consensus on the definition of causality and its possible mathematization (Pearl 2000). Possibly, the most common notion of causality refers to "causal connections between events which are the basic entities of causality " where "some of these events are causes and some are effects" (Sun 1994). Many authors (Hume 1890, Russell 1912, Russell 1948, Williamson 2004, among others) have analyzed the relation between causes and effects; the predominant school of thought reduces causation to a physical relation (either deterministic or probabilistic) between two different events. Moreover, in a long chain of causality where, often, latent conditions prior to the evident accidents sequence exist "one person's cause (i.e. what one person identifies as a "cause") is another person's consequence" (Bakolas & Saleh 2011). As underlined in this work, the distinction between causes and consequences is not always clear and meaningful; different "layers of understanding" may be applied to the notion of causality. In other words, the cause-effect implication relation can be thought of as a first level representation of causation. By "double-clicking" the link between events, the in-depth layers of causality surface, allowing a better comprehension and distinction of the causality nature.

In order to give a description of the nature and role of this relation we will exploit two metaphors coming from the Force Dynamics context and from Biochemistry. We will then distinguish between Agonist, Antagonist and Inverse Agonist actions. Intuitively, the different natures of these actions will influence the system's trajectory, making the accident's unfolding more or less likely. Before looking at the metaphors, it is then fundamental to introduce the concept of state trajectory and risk escalation/de-escalation, as those concepts constitute a basic framework for relevant applications of causal relations to engineering systems.

Table 1: Classification of major accident models

Model	Main Features
Sequential Heinrich (1941) Heinrich et al. (1980)	**Iceberg metaphor**: views accidents as the natural culmination of a series of events and circumstances where disasters are only the tip of the iceberg. **Domino metaphor**: introduces the notion of “initiating event”. The removal of one element in the causal chain is sufficient to the prevention of the incident.
Epidemiologic Gordon (1949) Hollnagel (2002)	**Spread of a disease metaphor**: extends the view of causality by incorporating new factors (active and latent conditions) in the description of the accident etiology. Environmental conditions for both humans and technologies are considered as a setting that could lead to an accident.
Energy transfer Haddon (1973) Reason (1997) Ale et al. (2010) Saleh et al. (2010)	This model views an accident as an unwanted transfer (or release) of energy. It is at the base of the current “Defense-in-Depth” (or “Layers of protection”) accident prevention strategy. **Swiss Cheese metaphor**: represents the defenses against accidents escalation through a series of safety barriers (slices of cheese) which possess individual weaknesses varying in position and size from slice to slice.
Systemic Sheridan (1992) Rasmussen (1997) Leveson (2004)	**Open- and close- loop metaphors**: view safety as the desired state output of a controlled system and accidents as deviations from this desired state. Deviations correspond to external perturbations of the system. Accident prevention is achieved through the solution of a control problem, with safety constraints, control actions, and (possibly) adequate feedback.

3 A NEW METAPHOR FOR ACCIDENT CAUSATION

In the Defense-in-Depth model, a series of barriers are placed along an accident trajectory to prevent the escalation of off-nominal conditions and ultimately the unfolding of an accident. The notion of depth is characterized by the multiplicity and the redundancy of the safety barriers along the risk state trajectory, as shown in Figure 1 (left).

This model takes into account only the possibility of a defensive action: the barrier interposed along the accident trajectory block the system’s transitions to higher risk state but leave the state in an off-nominal condition. Nothing is said about a possible offensive action that would lead to a change in the “riskiness” of the present state. This would open the possibility of risk de-escalation, through a transition to a new state less risky than the previous one, as shown in Figure 1 (right). Note that an offensive action is characterized by a change in the risk associated to the state and does not automatically imply a risk de-escalation, as suggested in Figure 2.

Based on this distinction, it is convenient to introduce the notions of *Agonist* and *Antagonist*, originally proposed by Talmy (2000) in the context of cognitive linguistics. Used in force-dynamics to indicate the opposing effects of two forces, Talmy relies on these terms to overcome some of the limitations of our own language and lexical structure in its way of representing causality. We will enhance this comparison by borrowing the concept of *Inverse Agonist* from biochemistry. In this context an agonist is viewed as a substance that binds to a receptor to induce a biochemical response; an antagonist, conversely, blocks the action of the agonist; finally, the inverse agonist is an agent that binds to the same receptor of the agonist, but produces an opposite response.

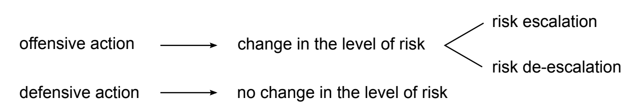

Figure 2: Taxonomy of offensive and defensive action strategy

In the context of accident causation, the notion of causality will be extended based on the presented metaphor of agonist/antagonist and inverse agonist actions. By using these notions as a metaphor to express the nature of action on the trajectory of the systems states, we will enable a distinction between finer primitives of causality.

3.1 *The definition of Agonist, Antagonist and Inverse Agonist for an accident trajectory*

In the context of accident causation, we relate the concepts of Agonist, Antagonist and Inverse Agonist to their effects on the system accident trajectory. An Agonist (a) is defined as an action applied to the system leading to a discrete transition of the state towards a higher risk level after a time t. Therefore, the system trajectory after an agonist action can be represented as in Figure 3 (left), where S_{i+1} is a riskier state than S_i.

An Antagonist ($\bar{a}$) is defined as an action applied to the system that blocks an agonist action. Therefore, the system is blocked in a stationary risky state after a time t. Figure 3 (center) represents this situation, where the transition from S_i to S_{i+1} does not occur.

Finally, an Inverse Agonist (ia) is defined as an action applied after a risk escalation of the system to overcome the effects of an agonist action, leading to a discrete transition of the state towards a lower risk level after a time t. Therefore, the system trajectory after an inverse agonist action can be represented as in Figure 3, where S_{i+1} is a riskier state than S_i and where S_{i+2} is less risky than S_{i+1}.

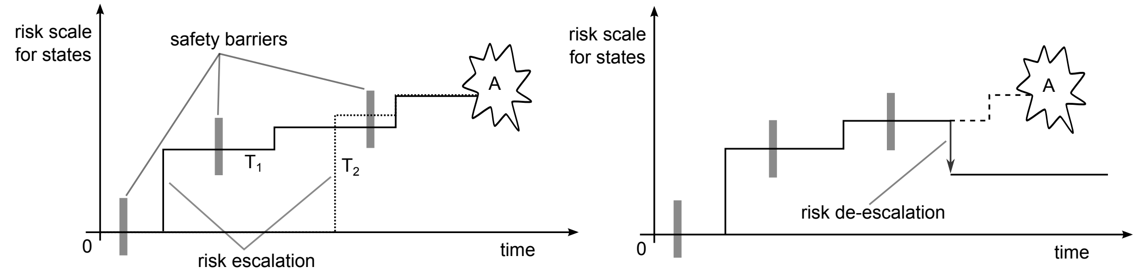

Figure 1: Concepts of defensive action principle (left) and risk de-escalation (right)

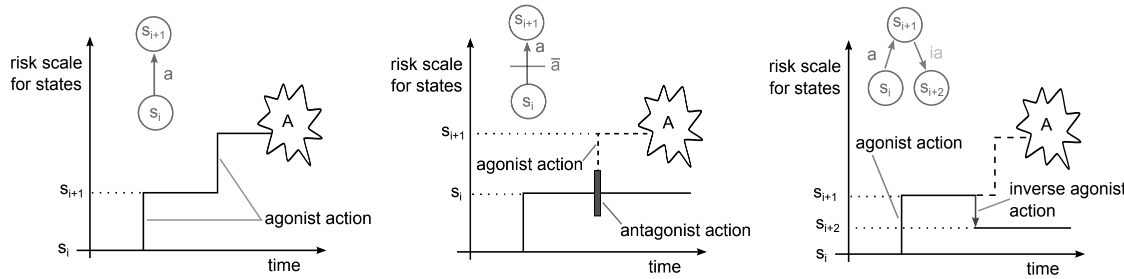

Figure 3: Discrete state space and effect on the accident trajectory for: agonist action (left), antagonist action (center), inverse agonist action (right)

Note that the notion of agonist, antagonist and inverse agonist should not be restricted to the idea of physical actions on the system (e.g. pushing an emergency button, or a fire wall). Saleh et al. (2010) highlight the different safety levers that exist and can be acted upon to prevent an accident unfolding. In this broader sense, an action can be referred to as a to a regulation, a maintenance operation, or even an economic incentive or an educational initiative.

The presented concepts allow a generalization of the traditional notion of causality, detailing causation into finer primitives, as presented in the next section.

3.2 *The primitives of causality*

In his study on force dynamics in language and cognition, Talmy (2000) identifies recurring patterns of physical interaction leading to a change of the system state. We extend some of these concepts to accident causation and relate them to direct effects on the system states' trajectory. The definitions of agonist, antagonist and inverse agonist provided in the previous section presume that those actions fulfill their goals (e.g. the antagonist action succeeds in blocking the agonist action). This is not always the case. Moreover, looking at the different possible interactions between them allows us to distinguish finer primitives of causality. These primitives provide in turn a framework to broaden the "cause-effect implication" relationship.

3.2.1 *Interactions between Agonist and Antagonist actions:*

- *Direct Causation:* This primitive originates from an unimpeded agonist action pushing the system to a riskier state. The causal relationship between the cause "agonist action" and the effect "risk-escalation" is defined as direct causation primitive of causality (Fig. 4).

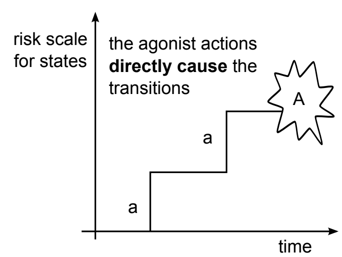

Figure 4: Direct Causation primitive of causality

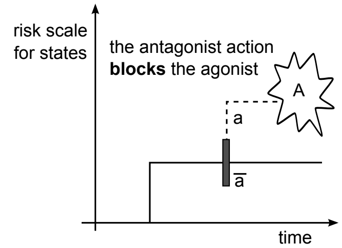

Figure 5: Blocking primitive of causality

- *Blocking:* This primitive originates from the presence of both an agonist and an antagonist action on the system, with an antagonist action stronger than the agonist force. The causal relationship between the cause "agonist and antagonist action" and the effect "blocked risk-escalation" is defined as blocking primitive of causality (Fig. 5).

- *Despite:* This primitive originates from the presence of both an agonist and an antagonist action on the system, with an agonist action stronger than the antagonist force. The causal relationship between the cause "agonist and antagonist ac-

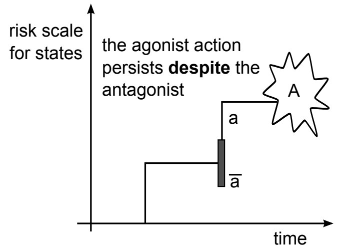

Figure 6: Despite primitive of causality

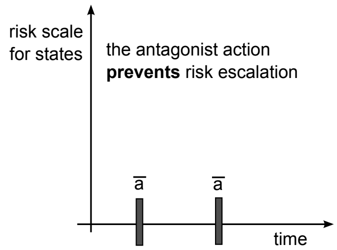

Figure 7: Prevention primitive of causality

tion" and the effect "unblocked risk-escalation" is defined as despite primitive of causality (Fig. 6).

- *Prevention:* This primitive originates from the presence of an antagonist action with no occurrence of an agonist action. The effect of a stationary persistence of the system in its nominal condition defines the prevention primitive of causality (Fig. 7).

- *Fragilizing:* This primitive originates from the absence of an agonist action and the removal of an antagonist action. The causal relationship between the cause "removed antagonist action effect "unblocked risk-escalation with the system persisting in its nominal condition is defined fragilizing primitive of causality (Fig. 8).

- *Letting:* This primitive originates from the presence of an agonist action and the removal of an antagonist action. The causal relationship between the cause "agonist and removed antagonist action and the effect "unblocked risk-escalation is defined as letting primitive of causality (Fig. 9).

We can summarize the interactions of agonist and antagonist leading to the distinction of primitives of causality as in Figure 10. The x-axis represents the presence or the absence of an Agonist, and the y-axis

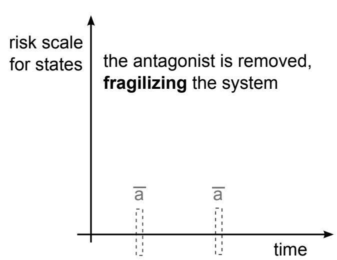

Figure 8: Fragilizing primitive of causality

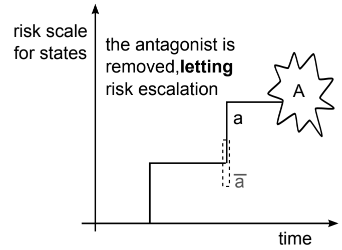

Figure 9: Letting primitive of causality

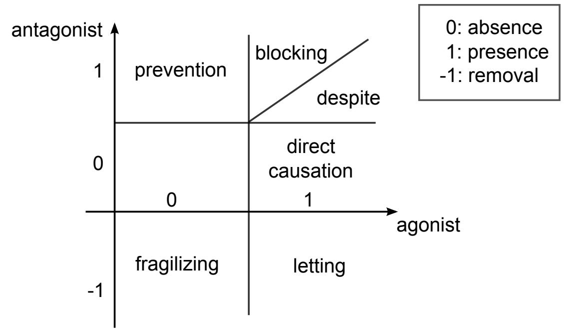

Figure 10: Primitives of causality derived from Agonist and Antagonist interactions

represents the presence, absence or removal of an Antagonist.

3.2.2 *Interactions between Agonist and Inverse Agonist actions:*

By definition of inverse agonist, this category of actions requires the occurrence of an agonist action. Primitives of causality can hence be derived only for the case of presence of the agonist. Note also that even if the inverse agonist differs by nature from the antagonist action, they share the primitives of direct causation, despite and letting. However, the blocking primitive is now replaced by:

- *De-escalation:* This primitive originates from the presence of both an agonist and an inverse agonist action on the system, with the inverse agonist action stronger than the agonist force. The causal relationship between the cause "agonist and inverse agonist action and the effect "risk de-escalation is defined as de-escalation primitive of causality (Fig. 11).

Also in this case, it is possible to summarize the primitives of causality derived from the interactions between the agonist and the inverse agonist in a

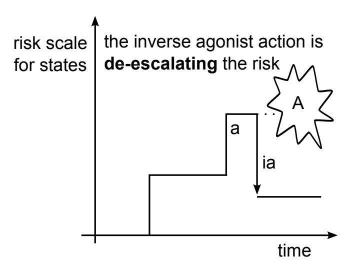

Figure 11: De-escalation primitive of causality

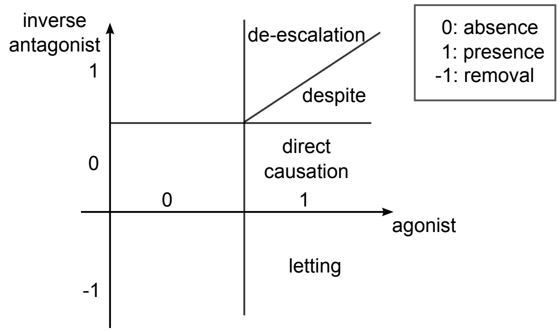

Figure 12: Primitives of causality derived from Agonist and Inverse Agonist interactions

graphic table, as shown in Figure 12. The x-axis represents the presence or the absence of an Agonist, and the y-axis represents the presence, absence or removal of an Inverse Agonist.

The plurality and co-existence of primitives of causality are the local or micro-causal mechanisms that explain an accident sequence. Causality in accidents is then represented as a web of primitives of causality instead of a traditional linear chain approach.

We believe that the primitives of causality here introduced allow a deeper understanding of causal mechanisms involved in system accidents and provide a richer basis for conceiving and articulating accident prevention.

3.3 *A risk metric for the accident trajectory*

The introduced methaphors of agonist, antagonist, and inverse agonist rely on the possibility to define a risk metric for the accident trajectory. This metric would allow a ranking of the states that compose such accident trajectory in terms of hazardousness or "riskiness". Due to the limited scope of this paper, we only present here the major steps to achieve such a goal.

1. *A definition of risk:* the adopted definition needs to be quantifiable in mathematical terms. An example is the definition provided by Kaplan & Garrick (2006) where risk is defined by three main ingredients: a scenario of occurrence; the probability associated to the occurrence of that scenario; the evaluation of the consequences of that scenario.

2. *Identification of scenarios and states:* this step requires a formal definition of initial state and scenario. Event driven discrete representation provides a useful technique, as indicated in (Saleh, Saltmarsh, Favarò, & Brevault 2013).

3. *Calculation of the probability associated to a scenario:*many techniques exist also in this case. Conditional probabilities for the transitions between the states composing the scenario would be required in this process.

4. *Definition of a quantifiable metric:* this step represents the core of the analysis. Different metrics correspond to different definitions of risk and of states/scenario. An example could derive from a TOPSIS technique based on the probability and the consequences associated with each scenario. This topic provides a fruitful venue for future investigation.

4 APPLICATION TO AN ACTUAL ACCIDENT TRAJECTORY: THE PIPER ALPHA EXPLOSION

In this section we analyze part of an actual accident trajectory to illustrate the use of the agonist, antagonist and inverse agonist metaphor, and to allow for an extension of the expression of causality through the introduction of the primitives of causality. The objective of the section is not to analyze why or how the specific accident happened, but rather to highlight the use of the presented concepts for the sake of accident prevention.

On July 6^{th} 1988, a massive fire and subsequent explosions destroyed the fixed offshore platform Piper Alpha, a gas and oil production facility in the North Sea. The accident claimed the lives of 167 out of the 248 workers on the platform that day (Whyte 2001). Several papers focused on the reconstruction of the accident and on detailed studies of the contributory causes of the accident (see, for instance, (Paté-Cornell 1993),(Drysdale & Sylvester-Evans 1998)). This example will concentrate only on two of the safety systems meant for accident prevention aboard the platform: the firewalls and the fire deluge system.

The Piper Alpha platform was composed of four Modules (A, B, C and D) connected by firewalls. The firewalls provided fireproof barriers to stop the progression of a fire between the different modules of the platform. More specifically, the firewall between Modules B and C and the one between Modules A and B were specified as a fire barrier up to 4.5 hours, while the firewall between Modules C and D was designed for up to a 6 hours fire (Drysdale & Sylvester-Evans 1998). The firewalls were not rated for explosion overpressure. The ignition point was located in Module C (Agonist action). The first ignition led to a risk escalation of the state of the platform. The firewalls acted as an Antagonist against the propagation of the fire (second Agonist action) to the adjacent modules. Several primitives of causality can be related to the firewall barriers. First of all, after the primary ignition, the firewall *blocks* the propagation of the fire acting against the propagation of the fire to the other module (Fig. 13).

At this point, note that there was no blowout panel to contain the explosion inside Module C. Therefore no Antagonist action existed against the propagation of the first explosion. The absence of the blowout

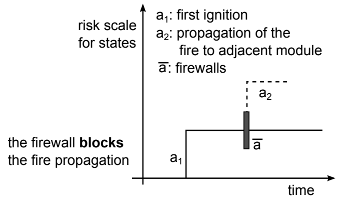

Figure 13: Firewall Antagonist action

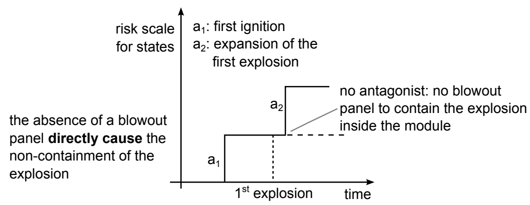

Figure 14: Absence of Antagonist: missing blowout panel

panel directly causes the non-containment of the explosion inside the module (Fig. 14).

Following the fireball originated from the first explosion, the firewalls failed as not designed against overpressure. The destruction of the firewalls *lets* the propagation of the fire to adjacent modules (Fig. 15).

The trajectory of the risky states of the system, considering only the firewall safety system, can be represented as in Figure 16. Several primitives of causality have been identified for the firewall system (direct causation, blocking and letting), allowing to highlight and distinguish the causes of the spread of the fire to other modules. This approach also underlines the absence of an important Antagonist (the blowout panel) to act against such propagation.

More generally, whenever a change in state is witnessed in the accident trajectory, the analyst can try to identify the involved agonist, antagonist and inverse agonist actions. In this case a risk escalation was not contrasted, highlighting the absence of the antagonist action.

We now turn our attention to the fire deluge system, an active fire protection measure consisting of a water supply system that provides adequate flow rate and pressure to sprinklers. In the event of fire, this system acts as an Inverse Agonist since its objective is to die down the fire and therefore decrease the riskiness of the systems state. In normal working conditions, the fire deluge system on the Piper Alpha should have de-escalated the risk state of the system after the first ignition. However, the deluge system of Module C had experienced repeated clogging and was inoperable at the time of the accident (Cullen 1993), yielding in

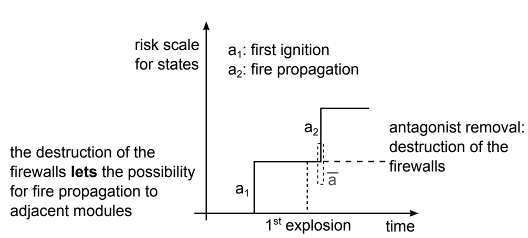

Figure 15: The removal of the Antagonist: destruction of firewalls

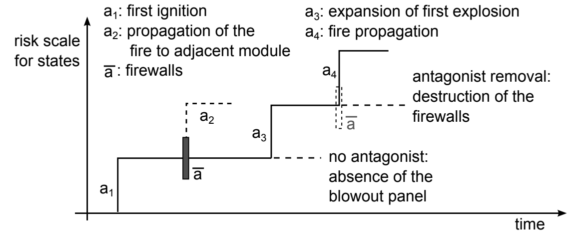

Figure 16: Accident trajectory analyzing the role of the firewall system

How can we prevent an accident from happening again?	Which agonist, antagonist, and inverse agonist are involved in the accident?
	Which antagonist and/or inverse agonist were missing/ ineffective in order to prevent the accident unfolding?
	Which primitives of causality are involved in the accident?
	What can we do about it?

Figure 17: Decomposition of the questioning process to prevent an accident

the end a limited effectiveness (Paté-Cornell 1993). Moreover, deluge systems were not installed in critical areas of the production module, *directly causing* the possibility of fire propagation to these areas.

The absence of antagonist actions as maintenance and detection of clogging of the fire deluge system allows a latent agonist (clogging existing long time prior the accident) to *directly cause* the subsequent agonist propagation of the fire in the adjacent modules. Furthermore, the system was ineffective in location where it had been installed *letting* the fire to expand, due to the turn off of the automatic pumps used to feed the fire deluge system (Paté-Cornell 1993). Thus, despite the presence of the Inverse Agonist (the deluge system), risk-escalation led to the accident unfolding.

This analysis not only reveals the "traditional type of causality" as the absence of blowout panel or the absence of fire deluge system in areas that caused the expansion of the fire, but also highlights other primitives of causality as letting or despite. On one hand this allows a descriptive point of view of causality by identifying the primitive of causality; on the other, it brings focus on the actions that define the accident trajectory by highlight the presence or the absence of Antagonist and Inverse Agonist to stop the risk escalation of the system or to de-escalate it.

5 CONCLUSIONS

Agonist, antagonist and inverse agonist concepts have been introduced to express the effects of different types of action on the system. This metaphor introduces a mechanistic approach of causality into the possible ways an action may modify a system trajectory. In this framework the causal relationship between events is reduced to interactions between agonists, antagonists and inverse agonists. Unimpeded agonist action pushes the system state on a trajectory of risk escalation. If agonist actions are sustained over time, they can lead to an accident. Antagonist action can block agonists and prevents risk escalation or further advancement of an accident sequence. Inverse agonist action engages the system in risk de-escalation. The interactions between these agents allow expressing causality in terms of *direct causation, blocking, despite, letting, prevention* and *de-escalation* primitives. The metaphor here introduced allows deepening the concept of "temporal build-up" of precursors and contributing factors, by introducing a way to represent the "path" or trajectory of the system in terms of risky states. The expressivity of the metaphor also allows the introduction the notion of de-escalation and widens the safety barrier concept, which intrinsically embodies only the notion of escalation blocking. The result is a refocus of accident prevention to an adaptive dynamical defense against risk escalation. To this end, the argument proposed by Kletz (2012) on the necessity to give an answer to the question "how can we prevent an accident from happening again?" could be decomposed as in Figure 17. Causal mechanisms in system accidents are particularly important and should be carefully identified and assessed. We believe the metaphor of agonist, antagonist and inverse agonist and the primitives of causality offer a possibility to express new concepts and to widen the importance of the study of etiology in accident prevention. Causality in accidents is then represented as a web of primitives of causality instead of a traditional linear chain approach. We argued that the primitives of causality here introduced allow a deeper understanding of causal mechanisms involved in system accidents and provide a richer basis for conceiving and articulating accident prevention strategies. Finally, we provided a simplified example of application to an actual accident sequence, highlighting the use of the presented concepts for the sake of accident prevention. As a final remark, note that intersting areas for further development of the presented concepts have been presented, including the very rich area of a risk metric definition and application. We believe that the presented concept can serve to overcome some of the limitiations of our language in the expression of causality relations.

REFERENCES

Ale, B., P. Swust, & C. Gulijk (2010). *Metaphors and models. Reliability, risk and safety*. ISBN 978-0-415-60427-7.

Bakolas, E. & J. H. Saleh (2011). Augmenting defense-in-depth with the concepts of observability and diagnosability from control theory and discrete event systems. *Reliability Engineering & System Safety 96*(1), 184–193.

Cullen, L. W. (1993). The public inquiry into the piper alpha disaster. *Drilling Contractor;(United States) 49*(4).

Drysdale, D. & R. Sylvester-Evans (1998). The explosion and fire on the piper alpha platform, 6 july 1988. a case study. *Philosophical Transactions A 356*(1748), 2929.

Gordon, J. E. (1949). The epidemiology of accidents*. *American Journal of Public Health and the Nations Health 39*(4), 504–515.

Haddon, W. (1973). Energy damage and the ten countermeasure strategies. *Human Factors: The Journal of the Human Factors and Ergonomics Society 15*(4), 355–366.

Heinrich, H. W. (1941). *Industrial accident prevention, a scientific approach -2nd edition*. London: McGraw-Hill Book Company.

Heinrich, H. W., D. Petersen, & N. Ross (1980). *Industrial accident prevention - 5th edition*. MacGraw-Hill, New York.

Hollnagel, E. (2002). Understanding accidents-from root causes to performance variability. In *Human Factors and Power Plants, 2002. Proceedings of the 2002 IEEE 7th Conference on*, pp. 1–1. IEEE.

Hume, D. (1890). *A Treatise of Human Nature: Being an Attempt to Introduce the Experimental Method of Reasoning Into Moral Subjects; And, Dialogues Concerning Natural Religion*, Volume 1. Longmans, Green, and Company.

Kaplan, S. & B. J. Garrick (2006). On the quantitative definition of risk. *Risk analysis 1*(1), 11–27.

Kjellén, U. (2000). *Prevention of accidents through experience feedback*. CRC.

Kletz, T. (2012). *Learning from accidents*. Routledge.

Laflamme, L. (1990). A better understanding of occupational accident genesis to improve safety in the workplace. *Journal of Occupational Accidents 12*(1), 155–165.

Lehto, M. & G. Salvendy (1991). Models of accident causation and their application: review and reappraisal. *Journal of Engineering and Technology Management 8*(2), 173–205.

Leveson, N. (2004). A new accident model for engineering safer systems. *Safety Science 42*(4), 237–270.

Paté-Cornell, M. E. (1993). Learning from the piper alpha accident: A postmortem analysis of technical and organizational factors. *Risk Analysis 13*(2), 215–232.

Pearl, J. (2000). *Causality: models, reasoning and inference*, Volume 29. Cambridge Univ Press.

Rasmussen, J. (1997). Risk management in a dynamic society: a modelling problem. *Safety science 27*(2), 183–213.

Rasmussen, J., P. Nixon, F. Warner, J. Rasmussen, P. Nixon, & F. Warner (1990). Human error and the problem of causality in analysis of accidents [and discussion]. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences 327*(1241), 449–462.

Reason, J. T. (1997). *Managing the risks of organizational accidents*, Volume 6. Ashgate Aldershot.

Russell, B. (1912). On the notion of cause. In *Proceedings of the Aristotelian society*, Volume 13, pp. 1–26. JSTOR.

Russell, B. (1948). Human knowledge: Its scope and its limits. *New York: Simon &Schuster*.

Saleh, J., K. Marais, E. Bakolas, & R. Cowlagi (2010). Highlights from the literature on accident causation and system safety: Review of major ideas, recent contributions, and challenges. *Reliability Engineering & System Safety 95*(11), 1105–1116.

Saleh, J. H., E. A. Saltmarsh, F. M. Favarò, & L. Brevault (2013). Accident precursors, near misses, and warning signs: Critical review and formal definitions within the framework of discrete event systems. *Reliability Engineering and System Safety http://dx.doi.org/10.1016/j.ress.2013.01.006i*(pending pubblication).

Salmon, W. C. (1998). *Causality and explanation*. Oxford University Press, USA.

Sheridan, T. B. (1992). *Telerobotics, automation, and human supervisory control*. MIT press.

Sun, R. (1994). A neural network model of causality. *Neural Networks, IEEE Transactions on 5*(4), 604–611.

Talmy, L. (2000). *Toward a cognitive semantics, Vol. 1: Concept structuring systems.* The MIT Press.

Whyte, D. (2001). Learning the lessons of piper alpha? *Risk Management and Society 16*, 263.

Williamson, J. (2004). *Bayesian nets and causality: philosophical and computational foundations*. Oxford University Press.