



Pós-Graduação em Ciência da Computação



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An Algebra of Temporal Faults

Ph.D. Thesis



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Recife, PE

2017

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A Ph.D. Thesis presented to the Center for Informatics of Federal University of Pernambuco in partial fulfillment of the requirements for the degree of Philosophy Doctor in Computer Science.

Federal University of Pernambuco

Center of Informatics

Graduate in Computer Science

Supervisor: Alexandre Cabral Mota

Co-supervisor: Alexander Romanovsky

Recife, PE

2017

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An Algebra of Temporal Faults/ André Luís Ribeiro Didier– Recife, PE, 2017-
172 p. : il.(alguma color.); 30 cm.

Supervisor: Alexandre Cabral Mota

Co-supervisor: Alexander Romanovsky

Ph.D. Thesis – Federal University of Pernambuco
Center of Informatics
Graduate in Computer Science, 2017.

1. Fault Trees. 2. Dependability. 3. Fault Tolerance. 4. Fault Removal. I. Alexandre
Cabral Mota II. Alexander Romanovsky III. Universidade Federal de Pernambuco. IV.
Centro de Informática. V. Título

CDU 02:141:005.7

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Recife, PE
2017

I dedicate this thesis to Juliana, Luciana (pipoquinha), and Bianca (snowflake).

Acknowledgments

If I was afraid of the path, I wouldn't have got here.

Two men helped me to build this path far before I started my scholar journey: Roberto and Júnior. My two grandfathers couldn't see how far I got. My heart was with them all the time, but I was physically far away from them in their very last breath. May God have them in his arms.

It is now eleven years since I graduated. I met professors Alexandre and Augusto still during the Computing Science undergrad course. They have been present in my academic life ever since. Their comments, instructions, talks, even jokes, are what moulded my path to here. I have no words to express how much I thank them, specially Alexandre.

CNPq¹ and FACEPE² were keen to guarantee my existential needs. The former with the trip to Newcastle upon Tyne, and the latter during the time I stayed in Recife, before and after the trip.

I thank to Sascha Romanovsky for accepting me as his advisee while I was a Research Assistant of the COMPASS project. His comments, instructions, and knowledge were of great importance for this work.

My stay in Newcastle upon Tyne couldn't be as good as it was without the hospitality, useful discussions, and support of my colleagues at Newcastle University. A big THANK YOU to John Fitzgerald, Zoe Andrews, Richard Payne, Claire Smith, Dee Carr, Claire Ingram, my shared office colleague Anirban Bhattacharyya, and all other staff members.

I thank all friends my family and I made outside University, in Newcastle. Thanks to Kelechi Dibie and her family to welcome us for the Christmas' and new year's dinners. They were our family abroad.

Dr. Monica Oliveira dedicated a few minutes reporting her own experience as a PhD student. These minutes were very important in the last days of the writing process of this work.

I thank all my family for their patience to have me away in several family reunions, due to the time required to do this work. In special, my two girls and my wife.

¹ Sandwich Doctorate in Newcastle upon Tyne, grant 246956/2012-7.

² Doctorate scholarship, grant IBPG-0408-1.03/11.

“Mathematical reasoning may be regarded rather schematically as the exercise of a combination of two facilities, which we may call intuition and ingenuity.

(Alan Turing)

Resumo

A modelagem de falhas é essencial na antecipação de defeitos em sistemas críticos. Tradicionalmente, Árvores de Falhas Estáticas são empregadas para este fim, mas Árvores de Falhas Temporais e Dinâmicas têm ganhado evidência devido ao seu maior poder para modelar e detectar propagações complexas de falhas que levam a um defeito.

Em um trabalho anterior, mostramos uma estratégia baseada na álgebra de processos CSP e modelos Simulink para obter rastros (sequências) de falhas que levam a um defeito. A partir dos rastros de falhas nós descartamos a informação de ordenamento para obter expressões de estrutura para Árvores de Falhas Estáticas. Ao contrário de descartar tal informação de ordenamento, poderíamos usá-la para obter expressões de estrutura para Árvores de Falhas Temporais ou Dinâmicas.

No presente trabalho apresentamos: (i) uma álgebra temporal de falhas (com noção de propagação de falhas) para analisar defeitos em sistemas e provamos que ela é de fato uma álgebra Booleana, e (ii) uma lógica de ativação parametrizada para expressar comportamentos nominais e de falha, incluindo a modelagem de falhas a partir de uma álgebra e um conjunto de modos de operação. A álgebra permite herdar as propriedades de álgebras Booleanas, leis e técnicas de redução existentes, as quais são muito benéficas para a modelagem e análise de falhas. Com expressões na álgebra temporal de falhas nós permitimos a verificação de propriedades de segurança (*safety*) baseadas em Árvores de Falhas Estáticas, Temporais ou Dinâmicas. A lógica criada neste trabalho pode ser usada com outras álgebras além das apresentadas. Sendo usada em conjunto com a álgebra temporal de falhas, tem a intenção de ajudar os analistas a considerar todas as possíveis situações em expressões complexas com operadores relacionados ao ordenamento das falhas, evitando esquecer combinações de falhas sutis (porém relevantes). Além disso, nossa álgebra temporal de falhas trata operadores NOT, que têm sido deixados de fora em outros trabalhos. Nós ilustramos nosso trabalho com alguns estudos de caso simples, mas reais, fornecidos pelo nosso parceiro industrial, a EMBRAER.

Isabelle/HOL foi utilizado para a mecanização das provas dos teoremas da álgebra temporal de falhas.

Palavras-chave: Simulink, CSP, FDR, Fault Tree Analysis, Temporal Fault Trees, Dynamic Fault Trees, Isabelle/HOL, Pandora, Fault Injection

Abstract

Fault modelling is essential to anticipate failures in critical systems. Traditionally, Static Fault Trees are employed to this end, but Temporal and Dynamic Fault Trees have gained evidence due to their enriched power to model and detect intricate propagation of faults that lead to a failure.

In a previous work, we showed a strategy based on the process algebra CSP and Simulink models to obtain fault traces that lead to a failure. From the fault traces we discarded the ordering information to obtain structure expressions for Static Fault Trees. Instead of discarding such an ordering information, it could be used to obtain structure expressions of Temporal or Dynamic Fault Trees.

In this work we present: (i) an algebra of temporal faults (with a notion of fault propagation) to analyse systems' failures, and prove that it is indeed a Boolean algebra, and (ii) a parametrized activation logic to express nominal and erroneous behaviours, including fault modelling, provided an algebra and a set of operational modes. The algebra allows us to inherit Boolean algebra's properties, laws and existing reduction techniques, which are very beneficial for fault modelling and analysis. With expressions in the algebra of temporal faults we allow the verification of safety properties based on Static, Temporal or Dynamic Fault Trees. The logic created in this work can be combined with other algebras beyond those shown here. Being used with the algebra of temporal faults it is intended to help analysts to consider all possible situations in complex expressions with order-related operators, avoiding missing subtle (but relevant) faults combinations. Furthermore, our algebra of temporal faults tackles the NOT operator which has been left out in other works. We illustrate our work on simple but real case studies, some supplied by our industrial partner EMBRAER.

Isabelle/HOL was used to mechanize the theorems proofs of the algebra of temporal faults.

Keywords: Simulink, CSP, FDR, Fault Tree Analysis, Temporal Fault Trees, Dynamic Fault Trees, Isabelle/HOL, Pandora, Fault Injection

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List of abbreviations and acronyms

AADL	Architecture Analysis and Design Language pp. 29, 115, 116
AL	Activation Logic pp. 15, 32–35, 95–101, 103, 106–108, 115, 116
AFP	archive of formal proofs p. 74
ATF	Algebra of Temporal Faults pp. 15, 25, 32–35, 43, 59, 71, 77–81, 84, 87–91, 93, 95, 96, 103–105, 109, 112, 113, 115, 116, 127, 142–144, 148–151, 153, 155, 157, 159, 161, 163, 165–169
BDD	Binary Decision Diagram pp. 15, 27, 30, 31, 43, 47, 53, 56–60, 62, 115
BN	Bayesian network p. 53
CML	COMPASS Modelling Language p. 40
CPN	coloured Petri-net p. 53
CSP	Communicating Sequential Processes p. 40
CSP_M	Communicating Sequential Processes pp. 30, 33, 43, 69, 71, 77, 93
CTMC	continuous-time Markov chain pp. 31, 53
DBN	dynamic bayesian network p. 31
DD	Dependence Diagram p. 41
DFT	Dynamic Fault Tree pp. 17, 28–32, 37, 41, 43–45, 48, 50–56, 59, 60, 71, 77, 84, 95, 115, 116
DNF	disjunctive normal form pp. 44, 50, 53, 58, 60, 84, 115
DRBD	Dynamic Reliability Block Diagram p. 41
DT	dependency tree pp. 30, 50, 51, 56, 58, 59
DTMC	discrete-time Markov chain pp. 31, 41, 51, 56
EMP	electromagnetic pulse p. 41
FBA	Free Boolean Algebra pp. 27, 30, 32, 43, 55, 61, 74, 77, 78, 80, 81, 104, 115
FDR	Failures and Divergences Refinement pp. 30, 69, 71
FMEA	Failure Modes and Effects Analysis pp. 31, 41
FSM	Finite State Machine p. 56
FT	fault tree pp. 15, 27–33, 35, 37, 38, 40, 43–46, 48, 50, 51, 54, 55, 62–67, 71, 77, 89, 93
FTA	Fault Tree Analysis pp. 15, 27–31, 33–35, 43–46, 63, 89
HCAS	cardiac assist system p. 54
HiP-HOPS	Hierarchically Performed Hazard Origin and Propagation Studies pp. 29–31, 38, 45, 71

HLPN	high-level Petri-net p. 56
HOL	higher-order logic p. 74
Isar	Intelligible semi-automated reasoning pp. 43 , 74
ITL	Interval Temporal Logic p. 56
LTL	linear temporal logic p. 48
MCS	minimal cut set pp. 27 , 44 , 47 , 50 , 53
MCSeq	minimal cut sequence pp. 24 , 29 , 33 , 49 , 50 , 53 , 56 , 58 , 59 , 89 , 93 , 116
PN	Petri-net p. 39
ROBDD	Reduced Ordered Binary Decision Diagram pp. 56 , 57
SBDD	Sequential Binary Decision Diagram pp. 31 , 53 , 56 , 60
SFT	Static Fault Tree pp. 15 , 28–30 , 32 , 37 , 41 , 43–48 , 50 , 53 , 55 , 56 , 58 , 59 , 61 , 62 , 71 , 77 , 84 , 95 , 115
SoS	System of Systems pp. 32 , 38
SWN	stochastic well-formed net p. 53
SysML	Systems Modelling Language pp. 32 , 40
TFT	Temporal Fault Tree pp. 28–30 , 32 , 37 , 43–45 , 48–53 , 55 , 56 , 71 , 77 , 84 , 95 , 115 , 116
TTT	Temporal Truth Table pp. 17 , 30 , 49 , 50 , 58
UML	Unified Modelling Language p. 40
Z	Z Notation pp. 56 , 74
ZBDD	Zero-suppressed Binary Decision Diagram pp. 56 , 59

Fault tree gates

AND	\wedge . Used in SFT , TFT , and DFT . pp. 27, 28, 43, 44, 46, 48, 50, 53, 54, 60, 62, 63, 71, 73, 84–86, 91, 93
CSp	cold spare. Used in DFT . pp. 29, 44, 52, 54, 56, 60
FDEP	functional dependency. Used in DFT . pp. 29, 44, 52, 54
IBefore	inclusive-before. Used in structure expressions of DFT . pp. 53, 54, 60
NIBefore	non-inclusive-before. Used in structure expressions of DFT . pp. 53, 54
NOT	\neg . Used in non-coherent trees. pp. 29, 30, 33, 35, 43, 48, 51, 62, 63, 66, 80, 84, 87, 90, 103, 115
OR	\vee . Used in SFT , TFT , and DFT . pp. 27, 28, 43, 44, 46, 48, 50, 53, 54, 62, 71, 85, 86, 92
PAND	priority-AND. Used in SFT , TFT , and DFT . pp. 28, 43, 44, 48–50, 52, 54, 56, 60, 89, 90
POR	priority-OR. Used in TFT . pp. 48, 50, 53
SAND	simultaneous-AND. Used in TFT . pp. 48, 50, 52, 53
SEQ	sequence enforcing. Used in DFT . pp. 29, 44, 52, 54
SIMLT	simultaneous. Used in structure expressions of DFT . pp. 53, 54
WSp	warm spare. Used in DFT . pp. 29, 60
XBefore	exclusive-before. Proposed in this work. pp. 25, 77–81, 83–87, 93, 104, 105, 115, 142, 143, 169

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³ This variant “M” is the machine-readable version of CSP.

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1 Introduction

The development process of critical control systems requires the rigorous execution of guides and regulations [4, 5, 6, 7]. Specialized agencies (like **FAA**, **EASA** and **ANAC** in the aviation field) use these guides and regulations to certify such systems. Only upon certification such systems can be used in the real-world.

Safety is a property (measured both qualitative and quantitatively) of crucial concern on critical systems and it is the responsibility of the safety assessment process. To employ such a process, dependable systems' taxonomy and safety assessment techniques must be well defined and understood. Clarification of concepts of dependable systems can be surprisingly difficult when systems are complex, because the determination of possible causes or consequences of failures can be a very subtle process [8].

ARP-4761 [7] defines several techniques to perform safety assessment. One of them is Fault Tree Analysis (**FTA**). It is a deductive method that uses trees to model faults and their dependencies and propagation. In such trees, the premises are the leaves (basic events) and the conclusions are the roots (top events). Intermediary events use gates to combine basic events and each kind of gate has its own combination semantics definition. Fault trees (**FTs**) that use only \vee (**OR**) and \wedge (**AND**) gates are called *coherent fault trees* [9, 10, 11, 12, 13]. They combine events as *at least one shall occur* and *all shall occur*, respectively. To analyse **FTs**, their structures are abstracted as Boolean expressions called *structure expressions*. The analysis of coherent **FTs** uses a well-defined algorithm based on the Shannon's method to obtain *minimal cut sets* (**MCSs**) from the structure expressions, and a general formula to calculate the probability of top events. The **MCSs** are obtained by reducing structure expressions to a normal form, in which each term is a combination of variables (basic events) with conjunctive (**AND**) gates, and the terms are combined by disjunctive (**OR**) gates. These minimal terms are also called *prime implicants* or *minterms*. The Shannon's method originated a formalism to reduce structure expressions called Binary Decision Diagram (**BDD**) [14, 15]. Another approach to reduce structure expressions is to use a mathematical model—called **Free Boolean Algebra** (**FBA**) [16, pp. 256-266]—that uses sets of sets to represent Boolean expressions.

Although structure expressions are formulas with logical operators, they are formalisms to enable automatic **FTA**. As shown in [17], **FTs** are a much richer model enabling a visual indication of fault paths, and include description of subsystems as intermediate events.

Figure 1 shows how **FTA** is traditionally performed. It starts with an architectural model, then faults are identified and modelled in an **FT**. System requirements are identified

and are checked with FTA results. If the requirements are satisfied (accepted), the process ends and the modelled system may be implemented. Otherwise, fault tolerance patterns are used, adding or modifying the original architecture to improve dependability. The analyses are executed until system requirements are met. We call such system requirements of FT's *acceptance criteria*.

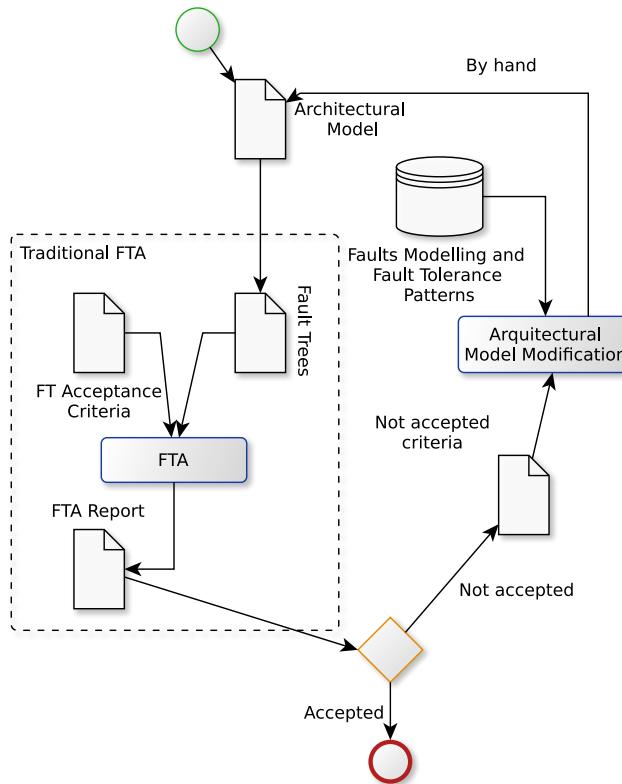


Figure 1 – Traditional FTA

Besides the traditional OR and AND gates, the Fault Tree Handbook [18] defines other gates as well. For example the priority-AND (PAND) gate, which considers the order of occurrence of events. Although the Fault Tree Handbook defines new gates, there is no algorithm to perform the analysis of trees that contain such new gates. This absence together with the need to analyse dynamic aspects of increasingly complex systems motivated the introduction of two new kinds of fault trees: Dynamic Fault Trees (DFTs) [1, 2] and Temporal Fault Trees (TFTs) [19, 20, 21]. These variant trees can capture sequential dependencies of fault events in a system. The difference from TFT to DFT is that TFTs use temporal gates directly, while DFT does not—DFTs gates are an abstraction of temporal gates. To differentiate the fault trees as defined in the Fault Tree Handbook from the other two, we will call the former as Static Fault Trees (SFTs).

The work reported in [20] aims at performing the full implementation of the Fault Tree Handbook, adding temporal gates to its Pandora¹ methodology. It was this

¹ Pandora stands for: P-AND-ORA, which translates to Priority AND, Time.

implementation that introduced the new concept of **TFTs**, cited previously. In such trees, events ordering is well-defined and an algebraic framework was proposed to reduce structure expressions to obtain minimal cut sequences (**MCSes**) and perform probabilistic analysis. Reducing expressions is also desirable to check for tautologies, for example.

 **DFTs** introduce ~~very different~~ gates to capture dynamic configurations of systems. The main gates are: cold spare (**CSp**), functional dependency (**FDEP**), and sequence enforcing (**SEQ**). The semantics of the first is to add “backup” events, so the gate is active if the primary event and all spares are active. The second adds basic events’ dependency from a trigger event. The third forces the occurrence of events in a particular order. There is also a warm spare (**WSp**) gate that is slightly different from the **CSp** gate. They differ on the nature of sparing, whether fast (warm, always-on) or slow (cold, stand-by). The readiness of the backup system in a **WSp** gate is higher than in a **CSp** gate. The work reported in [22] shows an algebraic framework to compositionally reduce **DFT** gates to order-based gates and perform probabilistic analysis of structure expressions. Thus, despite some limitations related to spare gates [23], the structure expressions used in **TFTs** and **DFTs** can be formulated in terms of a generic order-based operator.

The \neg (**NOT**) operator is absent in the algebras reported in [20, 21, 3, 24] because, if it is used without restrictions, it can be misleading, generating non-coherent analysis [11]. Although such an issue may arise, it can be essential in practical use as demonstrated in [9] with algebraic laws to handle the operator in structure expressions. Our concern is that the decision of the relevance of its use should be neither due to the choice of events-occurrence representation, as it is in [20, 21, 3, 24], nor with algebraic laws to include missing terms as it is in [9]. The algebra created in this work defines the **NOT** operator such that it can be used without any restriction (freely), as we show in Chapter 4.

Hierarchically Performed Hazard Origin and Propagation Studies² (**HiP-HOPS**) [25] is a set of methods and tools to analyse **FTs**. The semi-automatic generation of **FTs** has architectural models and failure expressions as inputs. *The failure expressions are in fact structure expressions of components or subsystems.* These expressions are annotated in components and subsystems and describe how they fail. The tool combines these expressions with regard to the architecture of the system to generate **FTs**. The work reported in [19] shows a strategy to use the semi-automatic **FT** generation of **HiP-HOPS** with Pandora to generate structure expressions of **TFTs**.

Architecture Analysis and Design Language (**AADL**) [26] is a standard language to model (among other features) system structure and component interaction. **AADL** has several tools to perform different analyses to obtain **SFT** to perform **FTA**. But **AADL**’s assertions framework does not express order explicitly as needed for **TFT** and **DFT** analyses.

² <<http://www.hip-hops.eu/>>

In previous work [27, 28], we proposed a systematic hardware-based faults identification strategy to obtain failure expressions as defined in **HiP-HOPS** for **SFTs**. We considered faults in components or subsystems to obtain structure expressions and use them as input for **HiP-HOPS**. If, instead, we obtain failure expressions of a whole system, they are in fact structure expressions of an **FT**. Our previous strategy throws away the ordering information of the fault event sequences to generate failure expressions for components or subsystems for **SFTs**. We focused on hardware faults because we assume that software does not fail as a function of time (wear, corrosion, etc). We inherited this view from our industrial partner, which assumes that functional behaviour is completely analysed by functional verification [29]. We followed industry common practices using Simulink diagrams [30] as a starting point. The work reported in [28] was based on Communicating Sequential Processes³ (**CSP_M**) to allow an automatic analysis using the model checker **FDR**. Thus, our strategy required the translation from Simulink to **CSP_M** [31]. It then runs **FDR** to obtain several counter-examples (which are fault traces) ending in failures. For two case studies provided by our industrial partner we showed that our automatically created failure expressions match with the engineer’s provided ones or are better because consider additional fault occurrence combinations.

1.1 Mathematical models

 Both **TFT** and **DFT** lack a first-order logic mathematical model like the one defined for **SFT**. For **SFTs**, mathematical models to reduce structure expressions are either based on set inclusion, with **FBA**, or through tree search, with **BDD**. One important concern on employing **FTA** is whether an **FT** indeed represents a system’s operational mode. The work reported in [32] exposes this concern for **DFTs**, and the **HiP-HOPS** framework—related to **SFTs** and **TFTs**—aims at getting this issue sorted out. Our contribution to this issue for **SFT** is shown in [28, 27].

The mathematical model for **TFT** has a discontinuity between states. The transition from the non-occurrence to an occurrence some time later is different from the occurrence of one event before another one. Such a discontinuity has some drawbacks as, for example, the impossibility to use **NOT** gates, and handling the specific case of non-occurrence with zeros in Temporal Truth Tables (**TTTs**). The reduction of structure expressions in **TFT** is based on a combination of: (i) algebraic rewriting—which can unfortunately result in an infinite application of rules, (ii) modularisation of independent subtrees (subtrees not always are independent), and (iii) dependency tree (**DT**) [33]—which are limited to seven basic events, due to exponential growth.

Most mathematical models [34, 35, 36] for **DFT** are based on the formalisation of

³ This variant “M” is the machine-readable version of **CSP**.

discrete-time Markov chain (**DTMC**) [37, 17] or continuous-time Markov chain (**CTMC**) [38, 39] because **DFTs** were initially conceived to be a visual representation of such models. As both **DTMC** and **CTMC** are state-based, they experience the state-space explosion problem. The works reported in [40, 41, 7] show techniques to overcome the state-explosion problem.

There are other approaches, as well. For instance, a modified version of **BDD** to tackle events ordering, called **Sequential Binary Decision Diagram (SBDD)** [42, 43], that can reduce structure expressions, and the work reported in [36], which proposes a conversion of **DFT** into **dynamic bayesian network (DBN)** [44] to perform probabilistic analysis.

The approach to tackle events ordering with **SBDD** [43] has two kinds of nodes: terminals and non-terminals (terminals are nodes with basic events, and non-terminals are nodes with two events and an operator). Although demonstrated in [45] that these unconventional nodes (non-terminals) generate correct and efficient Boolean analysis, the analysis is still dependent on the order-related operators because the relation of terminals and non-terminals is not established directly (non-terminals are seen as an independent node in [43]). For example, the occurrence of $A \rightarrow B$ is related to the occurrence of A and then B , but this relation is obtained in a further step, not in the **SBDD**.

The approach using the construction of **DBNs** [36] is automatic and handles time slices as $t + \Delta t$, which implies a notion of events ordering as well. As it is focused in probabilistic analysis, qualitative analysis is not directly supported.

The works reported in [3, 43] show that **DFT**'s operators can be converted into order-related operators, simplifying **DFT** analysis. Although the mathematical model presented in [3] establishes a denotational semantics for order-related operators, it lacks a formal method for expression reduction based on such a model. It defines, instead, several algebraic laws to reduce expressions and an algorithm to minimize the structure function.

HiP-HOPS proposes a hierarchical approach to model systems and perform **FTA** (and Failure Modes and Effects Analysis (**FMEA**) [46]). Although there is a tool to model and analyse systems using **HiP-HOPS**, **FTs** construction is based on an algorithm.

Another concern, left untreated in the literature, is the undesirable possibility of non-determinism in system analyses. For example, an **FT** to analyse a signal omission has the structure expression $A \wedge B$. Another **FT** to analyse a commission has the structure expression $(A \wedge B) \vee C$. In this example, if faults A and B are active, then either an omission or a commission is observed for the system.

1.2 Research questions

From the exposed in this section, our research questions are:

- RQ₁)* Is there a consistent mathematical model to analyse **TFTs** and **DFTs** that is set-based and similar to **FBA**?
- RQ₂)* What guarantees can we provide to detect non-determinism in erroneous behaviour? 

Also, does such a model:

- RQ₃)* represent systems behaviour by construction? 
- RQ₄)* allow both qualitative and quantitative analyses as supported by **TFT** and **DFT**?

1.3 Proposed solution

In this work we present an algebra, called **Algebra of Temporal Faults (ATF)**, to express ordering of fault events (**TFT** and **DFT**), enabling analysis of acceptance criteria of **FTs**. The laws of **ATF** are proven in a denotational semantics based on sets of lists of distinct elements. **ATF** aims at answering the research question *RQ₁*. The analysis of acceptance criteria is a decision problem and we use first-order logic and Isabelle/HOL 2015⁴ as verification tool.

System and fault modelling is an essential step towards safety analysis. Architectural modelling is the first step of the strategy and can be executed either in a graphical tool, or as requirements in natural language. For example, our work reported in [48, 49] uses fault modelling in Systems Modelling Language (**SysML**) [50] to verify fault tolerance of Systems of Systems (**SoSs**) [51].

Writing and analysing expressions with order-related operators is more complex than analysing expressions with Boolean operators only. We propose a logic, called **Activation Logic (AL)**, which works together with an accompanied (attached) algebra to perform analysis of system structure and component interaction with a focus on fault modelling and fault propagation, tackling the complexity introduced by order-related operators. **AL** receives an algebra and the set of operational modes of a system as parameters. The choice of algebra defines which structure expressions can be obtained: if Boolean algebra is passed as a parameter, the **AL** can generate structure expressions with Boolean operators (**SFT**); if the **ATF** is passed as a parameter, the **AL** can generate structure expressions with order-related operators (**TFT** and **DFT**). The **AL** requires that the accompanied algebras provide a set of properties (tautology and contradiction) and semantic values.

⁴ The 2002 tutorial is reported in [47], but there is a newer version published with the tool itself. The tool and the tutorial are available on their website at <<http://isabelle.in.tum.de>>.

 The use of the NOT is essential: besides its use in expressions, we use the complement of structure expressions, normalizing them and making them *healthy*.

To obtain critical event expressions used in **FTs** and to denote faults propagation, the **AL** provides a predicate notation and verification of non-determinism. We show three different approaches to check the non-determinism and answer research question **RQ₂**: (i) verify its existence, (ii) indicate which set of operational modes are active for a combination of faults, or (iii) which combination of faults activates a set of operational modes.

In our proposed solution, depending on the easiness to identify the faults, the analyst may follow one of the paths: (i) model the system in Simulink to allow fault injection and discovery, or (ii) model faults using the Activation Logic. Both paths end with structure expressions and the **FTA** is performed using **ATF**. 

Figure 2 shows how to perform **FTA** using faults injection. The “Faults injection” block is obtained from part of our work reported in [28, 27]. It starts with Simulink modelling, converts the model to **CSP_M** and then obtains fault event sequences (also called fault traces). The fault event sequences are then mapped to **ATF**, which has a denotational semantics based on sets of lists. This strategy aims at answering the research question **RQ₃**.

 Safety requirements are stated in terms of critical failures such as, for example, “the probability of a complete failure of an airplane engine should be less than 10^{-9} ” (quantitative), or “a complete failure of the propulsion system shouldn’t be caused by a single failure” (qualitative). Positive requirements such as, for example, “the communication system should be operational 99.99% of the cruise phase” are treated as a complement (the complete failure should have a probability in less than 0.01% of the cruise phase). The acceptance criteria analysis aims at answering the **RQ₄**. 

From the model in **ATF** (Figure 2), the acceptance criteria are then verified. If the criteria are accepted, the process finishes. Otherwise, the system is modified, and the process continues, modifying system’s architecture, using fault tolerance patterns, improving system’s dependability.

Figure 3 shows a faults modelling strategy directly in the **AL**. The **AL** associates each operational mode with a fault expression. After modelling all faults, the top events are extracted in a predicate notation. For example, “is the behaviour of the system in the operational mode X ?”, where X can be an omission, commission, etc. Given the flexibility of the **AL** notation, it can be used to reason about basic fault events and top-event failures, which are related to **RQ₁**. Each predicate in **AL** generates an expression in **ATF**, which is reduced to obtain a normal form to obtain MCSeqs and to calculate top-events probability. With the system modelled in **AL**, the fault tolerance patterns can be applied directly on

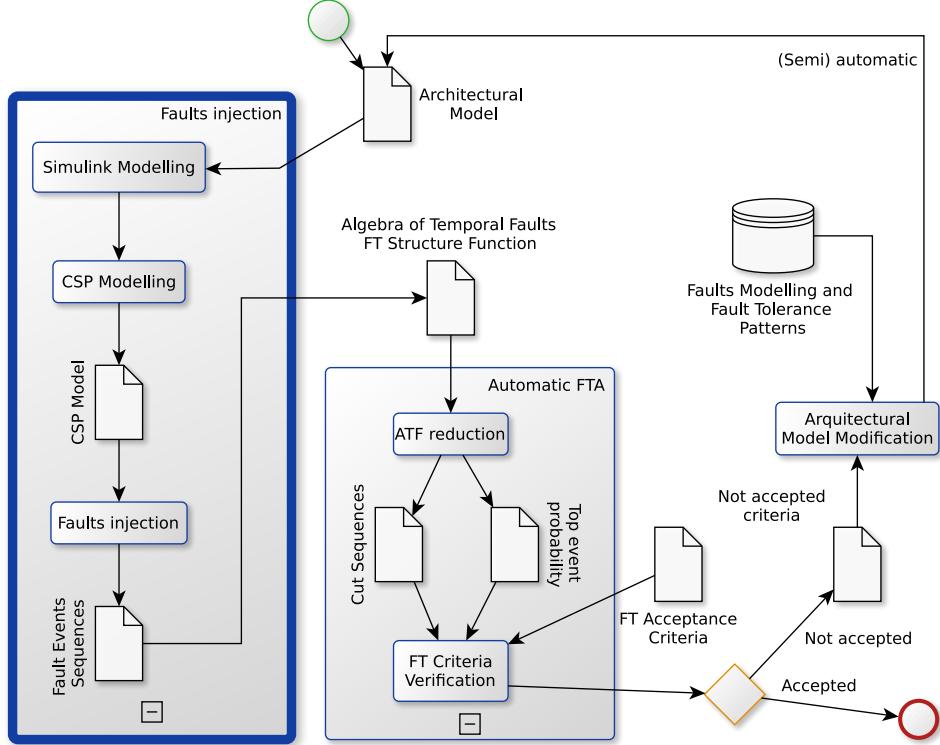


Figure 2 – Faults injection and ATF to perform FTA

the model.

The complete proposed solution is summarized in Figure 4, joining the paths described in Figure 2 and Figure 3 (paths A and B, respectively).

1.4 Contributions

The main contributions of this work are:

- C₁) Define a denotational and algebraic model to express fault events order with **ATF** (Chapter 4);
- C₂) Define a new operator to express order explicitly and proving that the resulting algebra—(**ATF**) using this operator and Boolean operators—is a conservative extension of the Boolean algebra (also published in [52])—see Chapter 4;
- C₃) From Simulink models, obtain fault event sequences and map them into **ATF** (Chapter 4);
- C₄) Reason about fault modelling in **AL** to obtain formal expressions of critical failures (top-event failures, Chapter 5);
- C₅) Illustrate both **ATF** and **AL** on a real case study, provided by our industrial partner (Chapter 6), and on a literature case study.

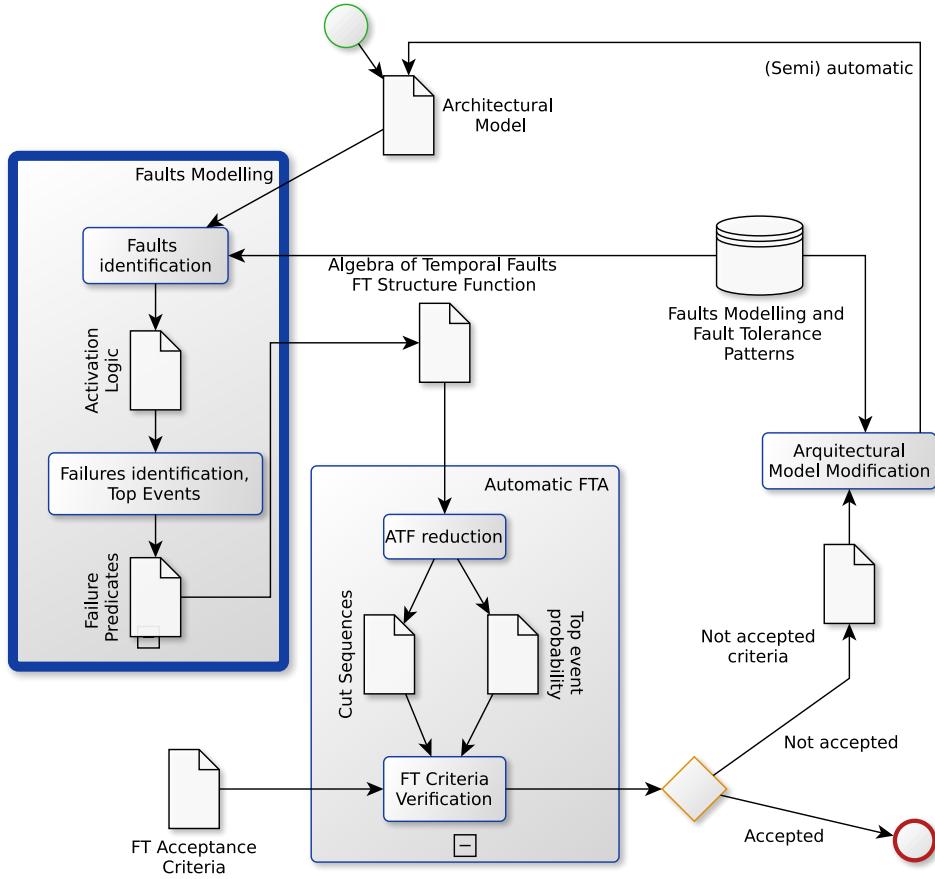


Figure 3 – AL and ATF to perform FTA

We use Isabelle/HOL, theories in Isabelle/HOL's library, and a theory in the AFP library [53] to prove the theorems of Chapter 4.

The case studies cover the following scenarios, presented in Chapter 6:

1. From a model in Simulink, obtain the failure expression of a critical failure, analyse the ordering relation of fault events, and verify its acceptance criteria;
2. Given a set of **FT** structure expressions, verify which fault combinations analysis are missing;
3. Perform a probabilistic analysis in an **FT** with an explicit **NOT** operator.

1.5 Thesis organization

This thesis is organized as follows: in Chapters 2 and 3 we show the concepts and tools used as basis for this work. Chapter 4 presents **ATF**, Chapter 5 presents **AL**, Chapter 6 the case study and the application of the proposed strategy, and we present our conclusions and future work in Chapter 7. The contributions presented in Chapter 4 are

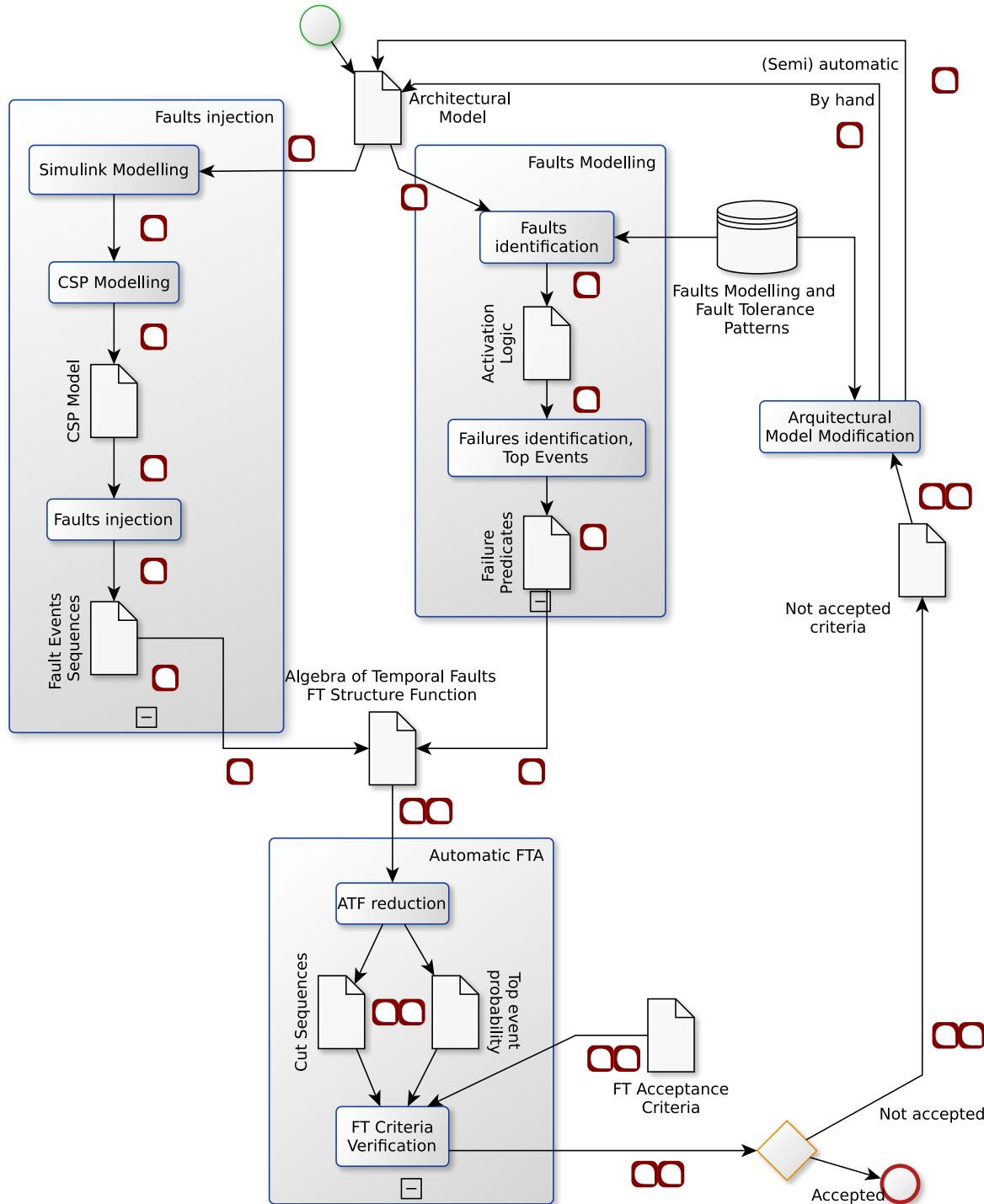


Figure 4 – Strategy overview

summarized in terms of proved results. To facilitate the understanding of the presented strategy, the effort to build laws and theirs (mechanized) proofs are shown in Appendix A.

Isabelle/HOL's theory files with all proofs are available at <<http://www.cin.ufpe.br/~alrd/phd/phd-alrd.zip>> (password: 6Zvq\$5Vyj).

2 Basic concepts

Means to dependability are obtained by modelling and analysing a system. It is strongly related to fault modelling, which depends on the kinds of analyses we want to perform. FTs are present in several stages of systems' modelling. We introduce dependability and fault modelling in Section 2.1.

An SFT is a snapshot of a faults' topology of a system, subsystem or component. The time relation of fault events in TFTs and DFTs allows the analysis of different configurations (or snapshots) of a system, subsystem or component. We discuss these time relations in Section 2.2.

2.1 Systems, dependability, and fault modelling

Computing systems are characterized by five properties: functionality, performance, cost, dependability, and security [8]. The work reported in [54, p. 289–302] explains these properties—including dependability—with a focus on software. Hardware and software are connected, as software faults may cause a failure in a software-controlled hardware, and hardware faults may send incorrect data, causing a failure in the software.

The work reported in [8] summarizes all concepts of (and related to) dependability for computing systems that contain software and hardware. In the following, we show these concepts and highlight those used in this work.

2.1.1 Systems

Before introducing systems' dependability, we first describe what a system is and its characteristics. A *system* is an entity that interacts with other systems (software and hardware as well), users (humans), and the physical world. These other entities are the *environment* of the given system, and its *boundary* is the frontier between the system and its environment.

The *function* of a system is what the system is intended to do, and its *behaviour* is what the system does to implement its function. The *total state* of a system are the means to implement its function and is defined as the set of the following states: computation, communication, stored information, interconnection, and physical condition. The *service* delivered by a system is its behaviour as it is perceived by its boundary. A system can both provide and consume services.

The *structure* of a system is how it is composed: a system is composed of components,

and each component is another system, etc. This concept of hierarchical compositionality in systems is what originated the concept of [SoS](#) and is the object of analysis in [HiP-HOPS](#). Such a recursion (of a system containing other systems) stops when a component—or a constituent system—is considered to be atomic. A system is the total state of its atomic components.

2.1.2 Dependability

The concepts that create the basis for dependability are: (i) threats to, (ii) attributes of, and (iii) means to attain.

Threats to dependability are the so-called *fault-error-failure* chain. A failure is a service deviation perceived on systems' boundary. An error is the part of the total state of a system that leads to subsequent service failure. Depending on how a system tolerate internal errors, many errors may not reach system's boundary. Finally, a fault is what causes an error. In this case, we say that the fault *occurred* (the fault is active). Otherwise, the fault is dormant, and has not occurred (yet). A *degraded* mode of a system is when there are active faults, so some functions of the system are inoperative, but the system still delivers its service.

There are two acceptable definitions of dependability reported in [8]. One is more general, difficult to measure: “the ability to deliver service that can justifiably be *trusted*”. A more precise definition that uses the definition of service failure is: “the ability to avoid service failures that are more frequent and more severe than is acceptable”. This definition has two implications about system's requirements: there should be defined how it can fail, and what are the acceptable severity and frequency of its failures.

The following systems' dependability attributes enlightens such requirements:

Availability: the readiness for correct service;

Reliability: continuity of correct service;



Safety: absence of catastrophic consequences on the environment (other systems, users, and the physical world). Safety can be verified using [FTs](#), which is part of the objective of this work;

Integrity: absence of improper systems alterations;

Maintainability: ability to be modified and repaired.

A system description should mention all or most of these attributes, at least the first three of them.

The implementation of these attributes requires a deep analysis of system's models. The *means to attain dependability* are summarized as follows:

Prevention is about avoiding incorporating faults during development.

Tolerance deals with usage of mechanisms to still deliver a—possibly degraded—service even in the presence of faults.

Removal is about detecting and removing (or reducing severity of) failures from a system, both in the development and production stages.

Forecasting is about predicting likely faults so they can be removed, or tackling their effects.

The intersection of the current work with dependability is in fault removal during development and fault tolerance (analysis). Following the taxonomy presented in [8], there are some techniques for fault removal, summarized as follows:

a) Static verification:

- Structural model:

Static analysis: Range from inspection or walk-through, data flow analysis, complexity analysis, abstract interpretation, compiler checks, vulnerability search, etc.

Theorem proving: Check properties of infinite state models.

- Behaviour model:

Model checking: Usually the model is a finite state-transition model (Petri-nets (PNs), finite state automata). Model-checking verifies all possible states on a given system's model.

b) Dynamic verification:

- Symbolic inputs:

Symbolic Execution: It is the execution with respect to variables (symbols) as inputs.

- Actual inputs:

Testing: Selected input values are set on system's inputs and their outputs are compared to expected values. The verification outcomes are observed faults, in case of hardware testing or software mutation testing, and criteria-based, in case of software testing.

Verification methods are often used in combination. For example, symbolic execution may be used to obtain testing patterns, test inputs can be obtained by model-checking

as in [55], faults can be used as symbolic inputs, and system behaviour can be observed using model-checking as in [28, 27] (This technique is called fault injection; see also [56]).

The techniques to attain fault tolerance are summarized as follows:

Error detection: is used to identify the presence of an error. It can be a concurrent or a preemptive detection. Concurrent detection takes place during normal service, while preemptive detection takes place while normal service is suspended.

Recovery: transforms a system state that contains errors into a state without them.

The behaviour of the system upon recovery is equivalent to the normal behaviour. Techniques range from rollback to a previously saved state without errors, error masking, isolation of faulty components, to reconfiguration using spare components.

In this work, we use a combination of: (i) fault-injection, (ii) theorem proving, and (iii) symbolic execution. We use these methods to obtain an erroneous behaviour of the system which is compared to the system dependability attributes (safety). We explain how these methods are combined in Chapter 4.



On the analyses of systems and its constituents, there is a distinction of operational modes and error events. Operational modes refer to the behaviour that is perceived on the boundaries of a system (*failure*). Error events, on the other hand, represent the behaviour detected in a constituent of a system. Such error events may relate to an operational mode, but not necessarily. Further in Chapter 4 we abstract these differences and leave the distinction as a parameter. We refer to such a set as *operational modes*.

2.1.3 Fault Modelling

Fault modelling plays an important role in reasoning about the fault-error-failure chain. They are the initial steps to perform the verification of a system, starting in the architectural model to reason about the critical failures, which are (in general) the top-events in FTs.

SysML is a profile for Unified Modelling Language (UML) that provides features to model structure and behaviour of systems. The works reported in [48, 49] define several structural and behavioural views in SysML to model the fault-error-failure chain and fault tolerance. Fault, error, failures, and fault propagation have structural views, which are related to behavioural views to describe fault activation and recovery. These works map SysML to two formal languages—COMPASS Modelling Language (CML) [57] and Communicating Sequential Processes (CSP) [58], respectively—to verify fault tolerance.

In [7] the safety assessment process for civil airborne systems and equipment describes development cycles and methods to “clearly identify each failure condition”. The

methods that involve failure identification are: (i) **SFT**, (ii) Dependence Diagram¹ (**DD**) [59, p. 198], (iii) **Markov chain**, and (iv) **FMEA**. The first three are top-down methods, that start with undesired failure conditions and move to lower levels to obtain more detailed conditions that causes the top-level event. **DDs** are an alternative method of representing the data in **SFT**. **FMEA** is a bottom-up method that identifies failure modes of a component and determines the effects on the upper level. We detail **SFT** in Subsection 3.1.1.

DFTs are an extension of **SFTs** and models dynamic behaviour of system faults. Similarly to the relation of **SFTs** and **DDs**, the work reported in [60] demonstrates the relation of **DFTs** to Dynamic Reliability Block Diagrams (**DRBDs**) [60]. As the models (**DFT** and **DRBD**) are equivalent, this work sticks to **DFT** due to the amount of work already published. We detail **DFTs** in Subsection 3.1.3.

2.2 Time relation of fault events

The most general case for time relations is to consider that each fault event has a continuous time duration. They are the basis on how fault events discretisation are defined. The point of view in this work is the analysis of the effects caused by a combination of faults in a snapshot of a system state. In Figure 5 we show all possibilities of events relations in a continuous time line from A to B (the converse relation is similar):

- a) A starts and ends before B starts;
- b) A starts before and ends after B has started, but before B has ended;
- c) A starts before B and ends after B has ended (A contains B);
- d) A and B start at the same time, but A ends before B;
- e) B starts after A, but they end at the same time;
- f) A and B start and end at the same time;
- g) A starts before B and ends when B starts.

Considering that fault occurrence corresponds to the start of a fault event and its duration, from Figure 5 we clearly identify which event comes first: A comes before B, except in the cases of items d) and f), where they start exactly at the same time. Even in the case of failures that have a common cause, there may be a slight fraction of time between failures. For example, an electromagnetic pulse (**EMP**) may cause a failure in all electronics, or a power shortage may cause a failure in all cooling systems in a power plant (see Fukushima accident [61]). There is a (temporal) causation relation of an **EMP** occurrence and the failures in all electronics, and also of a power shortage and the cooling systems's shutdown in Fukushima. On the other hand, there is no direct relation

¹ Also known as Reliability Block Diagram (**RBD**).

of the failure in each electronic, nor the failure in each cooling system. So, even if failure events have a common cause, and are not the same, they are *statistically independent*. The relations of items a) and g) shows the case that the system was repaired, thus A is not active when B starts.

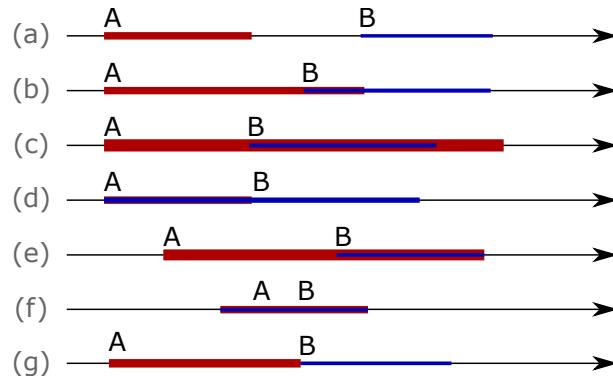


Figure 5 – Relation of two events with duration

In Chapter 4 we abstract the relation of events in continuous time as an *exclusive before* relation, based on fault *occurrence* (it is similar—at least implicitly—to what is reported in [20, 22]).

3 Analysis and tools

Structure expressions are used to analyse fault trees. In general, a structure expression comes from gates semantics and basic events. Basic events become variables and gates become operators (a gate may become one or more operators). In Section 3.1 we explain SFTs, TFTs, DFTs, and their respective structure expressions.

FBA_s and BDD_s are the basis to analyse structure expressions. Also, we were inspired by FBA concepts to create our Algebra of Temporal Faults (Chapter 4). We explain BDD_s and derived techniques in Section 3.2, and FBAs in Section 3.3.

The use of the Boolean operator *NOT*: (i) can be misleading, generating non-coherent fault trees [11], or (ii) can be essential in practical use [9]. We discuss such cases in Section 3.4.

In Subsection 3.4.3 we show the probability calculation of an FT with an explicit NOT operator.

To reuse a nominal model to analyse faults we need fault injection. In Section 3.5 we explain how we used Simulink and CSP_M to inject faults and obtain failure expressions from a nominal model.

Finally, in Section 3.6 we present basic usage of Isabelle/HOL and Intelligible semi-automated reasoning (Isar), which were essential to carry out the proofs presented in this thesis.

3.1 Fault Tree Analysis and structure expressions

FTA was introduced in the Fault Tree Handbook [18] with Static Fault Trees. FTA is a deductive method that investigates what are the possible causes of an unwanted event. The method starts with the top-level event as the unwanted event and the combination of lower-level events that can cause it. Events are combined using gates, and each gate has a well defined semantics. It continues until basic (atomic) events are reached. An SFT represents, in a single view—very often considering faults outside of the boundaries of a system—different states in which a particular failure (top event) is active in a system. The most traditional gates are AND and OR, which are equivalent to Boolean operators. These gates are also called coherent gates because they construct coherent trees (see Section 3.4 about the use of NOT gates). The Fault Tree Handbook shows other gates as, for example, the PAND gate, but the FTA with these gates is not well defined. SFT’s gates and analysis are detailed in Subsection 3.1.1.

TFTs were created aiming at fully implementing the Fault Tree Handbook. The **PAND** gate was first defined for **SFTs**, but its analysis was left open in the handbook. The semantics (and analysis) of **TFTs** is defined in terms of a denotational semantics based on *sequence values* to express ordering of events, thus tackling **PAND**'s order. We explain **TFTs** and the sequence values in Subsection 3.1.2.

With component and system design evolution, **DFTs** were created to tackle dynamic behaviour: fault-tolerance-related components (**CSp**), functional dependency (**FDEP**), and analysis of particular order of occurrence of faults (**SEQ**). **SFT**'s gates (as **AND** and **OR**) are part of **DFTs** as well. We explain them and **DFT**'s analysis in Subsection 3.1.3.

The structure of an **FT** (or the structure of an **MCS**, explained further) is represented with a formula. The variables represent occurrences of basic events. Unary and binary relation symbols capture the semantics of gates. A formula with these characteristics is called *structure expression* or *structure function* (as the expression depends on the variables). The semantics of a structure expression is that the top-level event occurs if some combination of basic events occur.

The results obtained from the **FTAs** are shown in the Fault Tree Handbook. We summarize them as:

a) Qualitative

MCSs: Minimal combinations of component failures causing system failure.

They are obtained from the reduction of structure expressions to a normal form. For example, in **SFTs**, structure expressions are reduced to disjunctive normal form (**DNF**). Each term in a reduced **DNF** is an **MCS**.

Importance: Qualitative rankings on contributions to system failure. A single fault causing a catastrophic failure is usually unacceptable. Ranking **MCSs** is the same as ordering them in ascending order of their size (smaller first).

b) Quantitative

Numerical probabilities: Probabilities of system and **MCS** failures. A system failure probability is obtained by assigning probabilities to basic events and then calculating it according to the gate semantics. **MCS** failure probability is the calculation of the probability of the occurrence of *all* basic events of a specific **MCS**.

Importance: Quantitative rankings on contributions to system failure. Ranking **MCSs** is the same as ordering them in descending order of some unreliability formula (higher first). These formulas used to quantify importance vary. The most common are: (i) system unavailability, and (ii) system failure occurrence rate.

Sensitivity evaluation: Modifying characteristics of components and evaluate their impact. For a particular event in a tree, a higher and a lower failure probability value are assigned. If the system unavailability is not changed, then such an event is not important—the system is not sensitive to such an event.

As stated in [62], there are other uses of FTA. One of great importance is using it to minimize and optimize resources, which has been object of study in HiP-HOPS [63]. Through importance measures, FTA not only identifies what is important but also what is unimportant. This removes components without impacting the overall failure probability, which is related to the quantitative importance and sensitivity evaluation.

In important stages of critical systems, FTA plays an essential role. At least three dependability means can be achieved by using FTs:

Removal. An FTA calculates the probability of failure of a subsystem. If such a probability is higher than a certain maximum reference, such a subsystem should be removed or left to be incorporated in combination with a more reliable component.

Tolerance. An FTA indicates whether a single fault—or fewer combinations than expected—could lead to a catastrophic failure. In this case, a system should have replication, or stages of fault detection and error handling. Also, the probability of failure of the chosen fault tolerance method can be evaluated.

In Subsections 3.1.1 to 3.1.3 we briefly show FT symbology and means to analyse FTs. We detail its structure expression extraction because they are a common means to perform both qualitative and quantitative analysis.

3.1.1 Static Fault Trees

SFT gates and structure expressions were used as basis for other kinds of trees, as in TFTs and DFTs. We explain their symbology and semantics in this subsection.

The Fault Tree Handbook shows traditional symbols for gates and events. Basic events are usually drawn as a rectangle (for the text) and a circle below it, as shown in Figure 6, or as a circle with the text of the basic event, as shown in Figure 7. Top-level and intermediary events are drawn as a rectangle (for the text) and a gate below it, as shown in Figures 6 and 7. When an FT becomes too large, transfer in and out symbols can be used. They are usually drawn as triangles with a letter or a number. Figure 7 depicts traditional gates as specified in the Fault Tree Handbook, and Figure 6 shows an FT using the Fault Tree Analyser¹—a free commercial tool. In this work, to keep a visual identity with other FTs, and to avoid symbol confusion, we use gate symbols as shown in Figure 8.

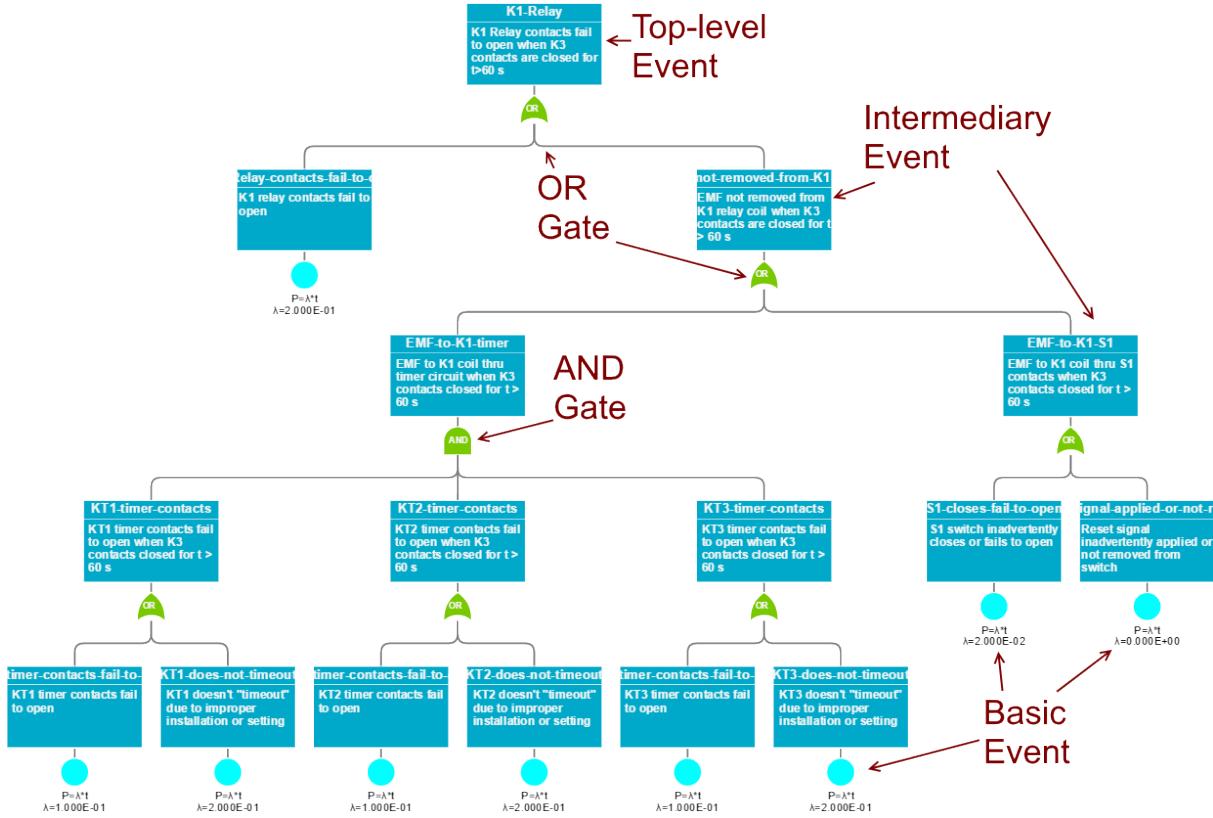


Figure 6 – SFT symbols using a free commercial tool

Structure expressions in FTA are defined in terms of set theory, using symbols for fault events occurrence. If a fault event symbol is in a set, then it means that this fault has occurred. A set is a combination of fault events that causes the occurrence of the top-level event of a tree. A structure expression of a tree is denoted by a set of sets of fault event combinations. The **OR** gate becomes the union operator between sets and the **AND** gate, the intersection. For example, if a system contains fault events *a*, *b*, and *c*, fault trees for this system contain at most all these three events. The occurrence of the fault event *a* is denoted by a set of sets *A*, which contains the following sets:

- $\{a\}$: only *a* occurs;
- $\{a, b\}$: *a* and *b* occur in any order;
- $\{a, c\}$: *a* and *c* occur in any order;
- $\{a, b, c\}$: all three events occur in any order.

All sets of *A* contain the fault event *a*. Similarly, the set of sets *B*—which represents the occurrence of *b*—contains all sets that contain the fault event *b* (it includes the set $\{a, b, c\}$, for example).

The fault tree in Figure 9 contains only two events and the resulting structure expression for this FT is the expression $A \cap B$ (*TOP*), where *A* and *B* are the sets of sets

¹ <http://www.fault-tree-analysis-software.com>, accessed 2/feb/2016

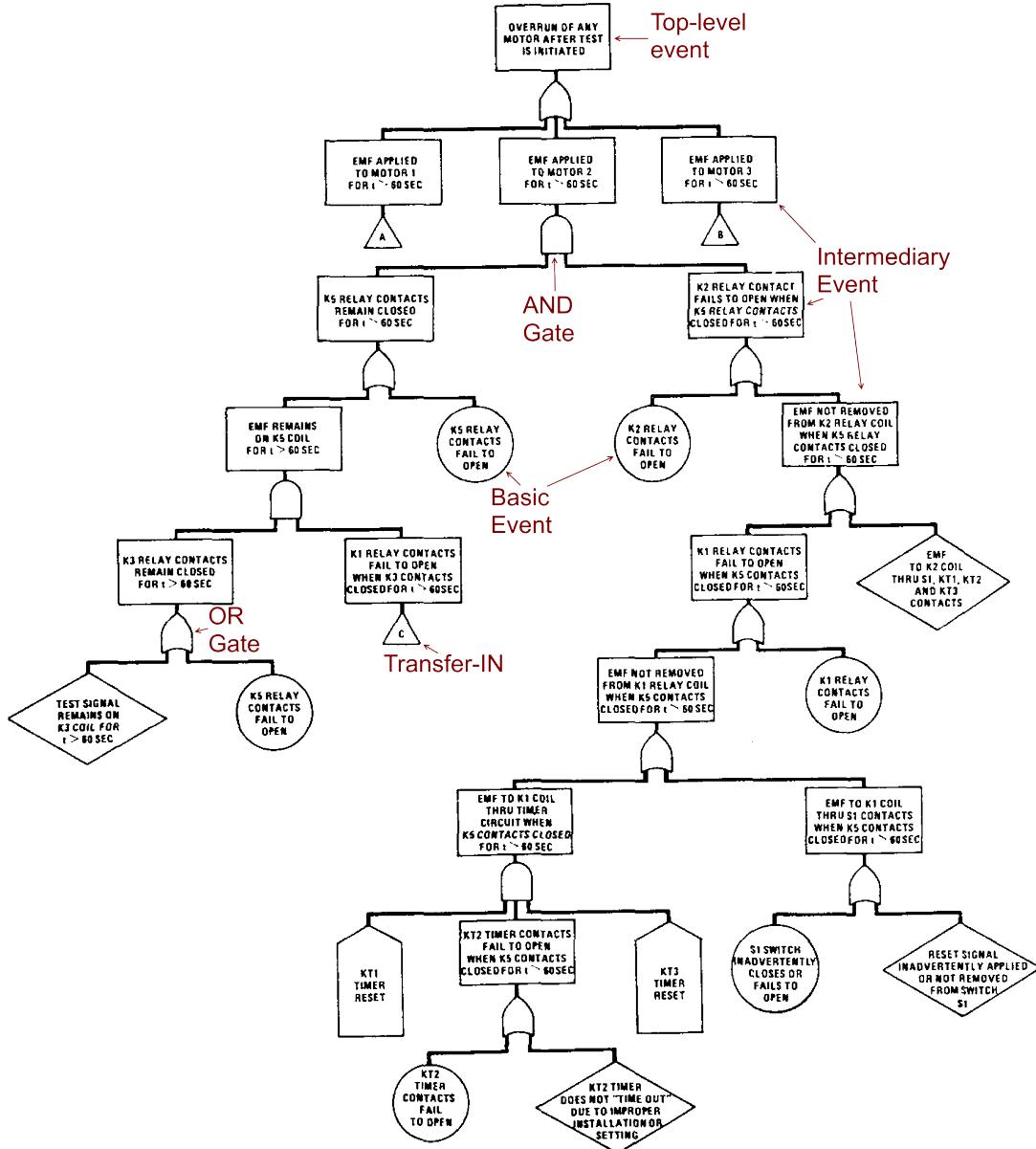


Figure 7 – SFT symbols as in the Fault Tree Handbook

that contain a and b , respectively. The resulting combinations for TOP are $\{a, b\}$ and $\{a, b, c\}$ (fault events a and b occur in all possibilities).

After obtaining structure expressions, the next step is to reduce the expressions to a normal form to obtain the *MCSs*, which are the sets that contain the minimum and sufficient events to activate the top-level failure. Probabilistic analysis is then performed on these events to obtain the overall probability of occurrence of the top-level event. The Fault Tree Handbook shows an algorithm based on Shannon's method to reduce structure expressions to obtain minimal cut sets. The Boolean expression of the tree shown in Figure 9 is $TOP = A \wedge B$. A technique called **BDD**—which derives from Shannon's method—is explained in Subsection 3.2.2.

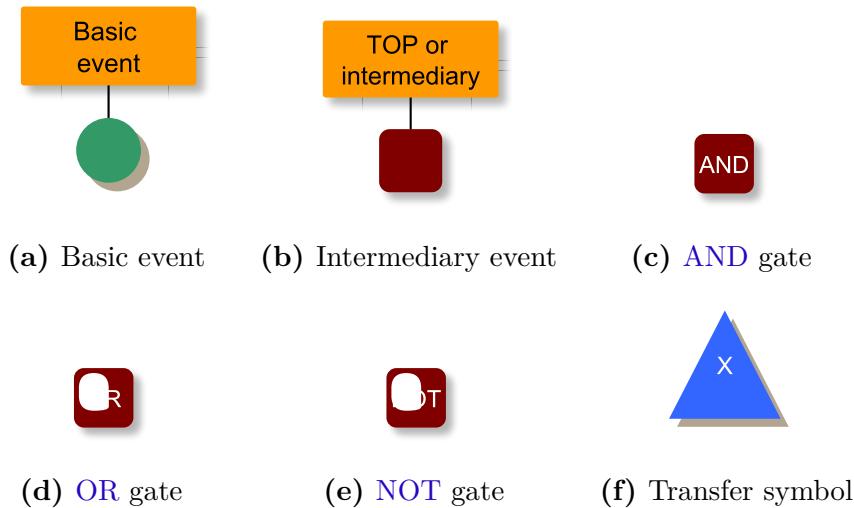


Figure 8 – SFT gates

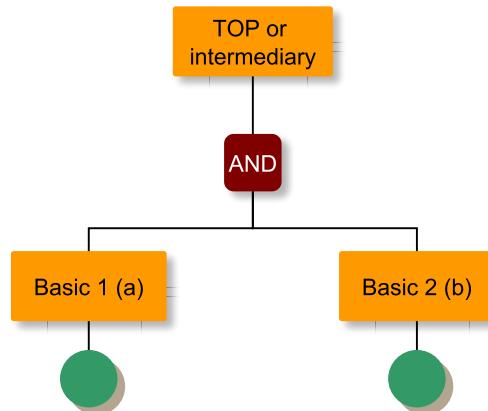


Figure 9 – Very simple example of a fault tree

3.1.2 Temporal Fault Trees

There are at least two versions of TFTs. One is described in [64] and uses a more traditional style of temporal logic (a variation of linear temporal logic (**LTL**)). The other version is called Pandora and is the one we refer to in what follows.

TFTs express ordering of events by directly focusing on ordering relationships rather than different states of a system. Basically they extend SFT's **PAND** gates, allowing analysis of FT with such gates. It is simpler to express than DFT, but lacks the fault-tolerance-related gate of DFTs (which we show in Subsection 3.1.3).

Structure expressions are also present in TFTs [20, 21, 33], through the Pandora methodology. These expressions use the SFT operators **OR** and **AND**, and three new operators² related to events ordering: priority-AND (**PAND**), priority-OR (**POR**), and simultaneous-AND (**SAND**). The semantics of the **PAND** in TFTs is similar to the

² In formulas, the following symbols are used to represent the operators, respectively: “<”, “|”, and “&”

semantics of the **PAND** described in the Fault Tree Handbook. To avoid ambiguous expressions, the semantics in **TFTs** is stated in terms of natural numbers, using a *sequence value* function. For every possible combination of events ordering, it assigns a sequence value to each fault event. For example, if event A occurs before event B, then the sequence value of A is lower than the sequence value of B, and one formula to express this is $A < B$.

An invariant on sequence values is that there are no gaps for assigned values. For example, if faults A and B occur at the same time and there are only these two events, then they should both be assigned value 1. On the other hand, if A occurs before B, then the assigned values are 1 and 2, respectively. The possible values increase with the number of variables to express the cases that all events occur in different times. For example, A occurs before B, and B occurs before C. In this case, the assigned values are 1, 2, and 3, respectively. Value zero means that the event is not active on the combination. Similar to Boolean's truth tables, the Pandora methodology defines **TTTs**. They represent formula values for every combination of events. Table 1 shows the **TTT** of all **TFT** operators according to the semantics described in terms of a sequence value function S as follows:

$$\text{[} \quad S(A \wedge B) = \begin{cases} \max(S(A), S(B)) & \text{if } S(A) > 0 \wedge S(B) > 0 \\ 0 & \text{otherwise} \end{cases} \quad \text{(3.1a)}$$

$$\text{[} \quad S(A \vee B) = \begin{cases} \min(S(A), S(B)) & \text{if } S(A) > 0 \wedge S(B) > 0 \\ \max(S(A), S(B)), & \text{otherwise} \end{cases} \quad \text{(3.1b)}$$

$$\text{[} \quad S(A < B) = \begin{cases} S(B) & \text{if } S(A) > 0 \wedge S(B) > 0 \wedge S(A) < S(B) \\ 0 & \text{otherwise} \end{cases} \quad \text{(3.1c)}$$

$$\text{[} \quad S(A | B) = \begin{cases} S(A) & \text{if } S(A) < S(B) \vee S(B) = 0 \\ 0 & \text{otherwise} \end{cases} \quad \text{(3.1d)}$$

$$\text{[} \quad S(A \& B) = \begin{cases} S(A) & \text{if } S(A) > 0 \wedge S(B) > 0 \wedge S(A) = S(B) \\ 0 & \text{otherwise} \end{cases} \quad \text{(3.1e)}$$

Figure 10 shows **TFT**-specific symbols used in this work. To illustrate **TFTs**, for the formula $(A < C) \vee (A \wedge B)$, we show: (i) the **TFT** in Figure 11, and (ii) its corresponding **TTT** in Table 2 (the column '# indicates the **MCS** number).

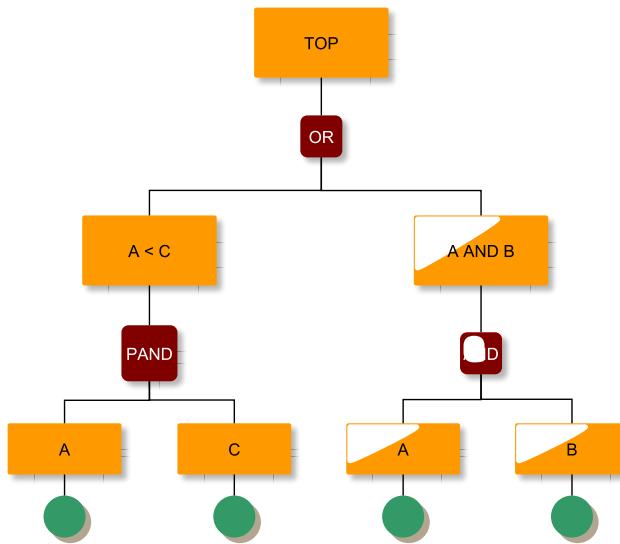


(a) **PAND** gate (b) **POR** gate (c) **SAND** gate

Figure 10 – TFT-specific gates

Table 1 – TFT’s operators and sequence value numbers

A	B	AND	OR	PAND	POR	SAND
0	0	0	0	0	0	0
0	1	0	1	0	0	0
1	0	0	1	0	1	0
1	1	1	1	0	0	1
1	2	2	1	2	1	0
2	1	2	1	0	0	0

**Figure 11 – TFT** small example

From structure expressions in order-sensitive **F**Ts (**TFT** and **DFT**), **MCSeqs** are obtained. Several approaches represent **MCSeq** ordering differently. For the best of our knowledge they are introduced in the work [65] similarly to **MCS**, allowing set elements with arrows (“ \rightarrow ”) to represent order.

For **TFTs**, in the work [21] **MCSeqs** are represented as a **DNF** using **AND** and the temporal operators (**PAND**, **POR**, and **SAND**) as doublets (a single temporal relation)—which are the minimal terms—or prime implicants—in the **DNF**. In a doublet, the expression is a product (**AND**) of temporal operators, and each temporal operator contains *exactly* two events. The conversion to doublets uses the temporal laws as shown in the work reported in [21]. For example, the expression $(X \& Y) | Z$ is a temporal relation (**POR**) of a temporal relation (**SAND**). To extract **MCSeqs** it needs to be converted to $[X \& Y] \wedge [X | Z] \wedge [Y | Z]$ (the square brackets is the doublets notation and the conversion is the definition of the *Temporal Distributive Law* [21, p. 120]).

The normal form for **TFT** is similar to that for **SFT**: it is a **DNF** with temporal operators (**PAND**, **POR**, **SAND**) in the minimal terms. The reduction of **TFT** structure expressions is achieved using **DT**. In a **DT**, if all children of a tree node are true, then the

Table 2 – TTT of a simple example

#	A	B	C	$A < C$	$A \wedge B$	$(A < C) \vee (A \wedge B)$
01	0	0	0	0	0	0
02	0	0	1	0	0	0
03	0	1	0	0	0	0
04	0	1	1	0	0	0
05	0	1	2	0	0	0
06	0	2	1	0	0	0
07	1	0	0	0	0	0
08	1	0	1	0	0	0
09	1	0	2	2	0	2
10	1	1	0	0	1	1
11	1	1	1	0	1	1
12	1	1	2	2	1	1
13	1	2	1	0	2	2
14	1	2	2	2	2	2
15	1	2	3	3	2	2
16	1	3	2	2	3	2
17	2	0	1	0	0	0
18	2	1	0	0	2	2
19	2	1	1	0	2	2
20	2	1	2	0	2	2
21	2	1	3	3	2	2
22	2	2	1	0	2	2
23	2	3	1	0	3	3
24	3	1	2	0	3	3
25	3	2	1	0	3	3

node is also true. Conversely, if a node is true, then all its children are also true. An issue with **DTs** is that they grow exponentially. According to the work reported in [33], it is already infeasible to deal with seven fault events in **TFTs**. Although there is a solution, it is based on a mixed application of **DTs**, modularisation of independent subtrees, and algebraic laws [20]. Such a solution is not able to solve **FTs** with **NOT** gates, and requires some manual work to modularise independent trees. We show **DTs** in Subsection 3.2.3. Some of these algebraic laws are:

$$(X < Y) \vee (X \& Y) \vee (Y < X) = X \wedge Y \quad \text{Conjunctive Completion Law} \quad (3.2a)$$

$$(X | Y) \vee (X \& Y) \vee (Y | X) = X \vee Y \quad \text{Disjunctive Completion Law} \quad (3.2b)$$

$$(X | Y) \vee (X \& Y) \vee (Y < X) = X \quad \text{Reductive Completion Law 1st} \quad (3.2c)$$

$$(X \wedge Y) \vee (X | Y) = X \quad \text{Reductive Completion Law 2nd} \quad (3.2d)$$

3.1.3 Dynamic Fault Trees

Dynamic Fault Trees were designed with the goal of analysing complex systems with dynamic redundancy management and complex fault and recovery mechanisms [1]. The idea was to create easy-to-use and less error-prone modelling tools than using **DTMCs**—or simply **Markov chains**—directly. So, since the very beginning, **DFTs** were intended to be a visual representation of **Markov chains**. Figure 12 depicts the original gate symbols as shown in [1, 2]. In this work, we use gate symbols as depicted in Figure 13. The informal semantics of them are:

FDEP: When the trigger event occurs, the dependent events are forced to occur. Timing in this gate between the trigger event and dependent events occurrences can be instantaneous (like in TFT's **SAND** gate), or a small amount of time, thus implying an order of occurrence, depending on the kind of dependency.

CSp: It is a specific gate to handle spare components. It is important to note that connected inputs are not components—they are fault events of connected components. If the i th input is already active (fault has occurred), then it is expected that the input $(i + 1)$ th is not, following the specified order. The output becomes true after all connected inputs become true. A spare event can be connected to more than one **CSp** gate, representing the spare unit connection to one or more components.

PAND: The same as in TFT: when the connected input events occur in the specified order, it outputs true.

SEQ: The connected events *shall* occur in the specified order. It is different from the **PAND** gate, because the latter *detects* the specified order. The usage of this gate is usually associated with **FDEP**.

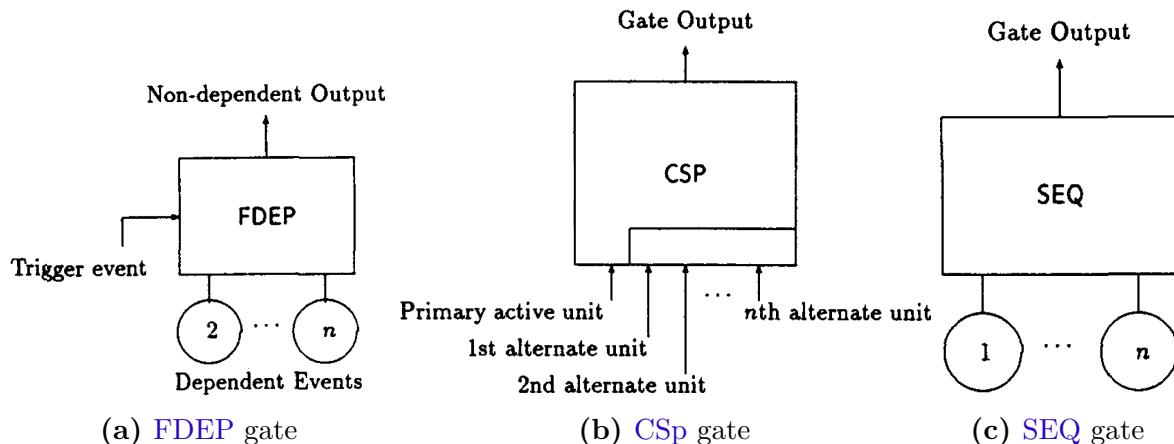


Figure 12 – DFT's original gates symbols

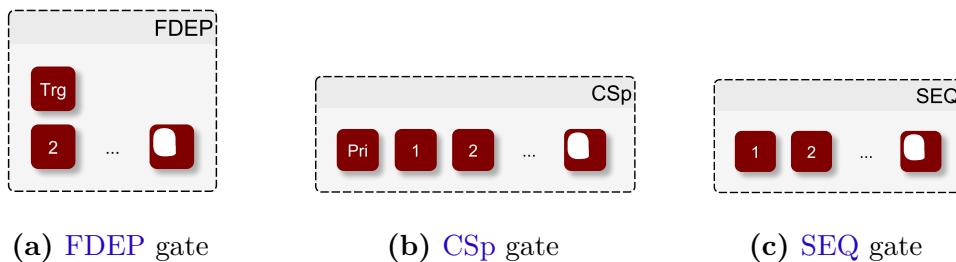


Figure 13 – DFT's gates symbols

There are several means to analyse DFTs qualitative and quantitatively. The works reported in [3, 66, 22, 23] use structure expressions to perform both qualitative and

Table 3 – DFT conversion to calculate probability of top-level event

Conversion	Calculation	Explained in
Automaton-like structure	CTMC	[35]
Bayesian network (BN) [67]	Inference algorithm (model-specific)	[36]
Stochastic well-formed net (SWN) [68] (a kind of coloured Petri-net (CPN) [69])	CTMC	[70]
SBDD (a modified version of BDD)	model-specific	[42, 43]

quantitative analysis, and the work reported in [23] summarizes other approaches. Table 3 shows more details about such approaches. We categorize them as:

- a) Finding MCSeqs (qualitative analysis) is obtained by replacing DFT gates with SFT gates, using the text as their logical constraints. MCSs in the SFT are expanded using timing constraints from the texts into MCSeq. In this case, the behaviour of spare events cannot be correctly taken into account;
- b) Quantitative analysis consists in converting a DFT to a well-defined formalism to calculate the probability of its top-level event. Table 3 shows the conversion options, the calculation, and where the method is explained.

In [3, 66, 22] fault events occur in a specific time and are instantaneous (similar to detected faults), stated through a “date-of-occurrence” function. As the “date-of-occurrence” function is stated in continuous time, the probability of two events occurring at the same time is negligible. Thus, the relation in time of the occurrence of the events is, in fact, the useful information. DFT gates’ algebraic model is summarized in Table 4. Structure expressions are written with an algebra that has operators OR and AND, and three new operators to express events ordering: (i) non-inclusive-before (NIBefore), (ii) simultaneous (SIMLT), and (iii) inclusive-before (IBefore). The NIBefore and the SIMLT operators are similar to TFT’s POR and SAND operators, respectively. The IBefore is a composition of NIBefore and SIMLT operators. Table 5 summarizes the date-of-occurrence function for all operators. An infinite value means the event never occurs.

MCSeqs are extracted from a normal form of structure expressions written in a DNF. Minimal terms are products of variables and NIBefore operators (the other operators can be written as combinations of NIBefore). The reduction of DFT structure expressions uses algebraic laws as, for example:

$$(a \triangleleft b) \vee (a \triangle b) \vee (b \triangleleft a) = a \vee b \quad (3.3a)$$

$$(a \wedge (b \triangleleft a)) \vee (a \triangle b) \vee (b \wedge (a \triangleleft b)) = a \wedge b \quad (3.3b)$$

$$(a \trianglelefteq b) \wedge (b \trianglelefteq a) = a \triangle b \quad (3.3c)$$

Table 4 – Algebraic model of DFT gates with inputs A and B

Gate	Algebraic model of gate's output	Note
FDEP	$A_T = T \vee A$ and $B_T = T \vee B$	A_T and B_T replace A and B on the resulting expression
CSp	$(B_a \wedge (A \triangleleft B_a)) \vee (A \wedge (B_d \triangleleft A))$	A is the active input, and B is the spare. Subscripts a and d represent component's state— <i>active</i> and <i>dormant</i> , respectively, which are used on the failure distribution formulas
PAND	$B \wedge (A \trianglelefteq B)$	No distinction of active or dormant states.

Table 5 – Date-of-occurrence function for operators defined in [3]

Operator	Expression	Expr. value if	Expr. value if	Expr. value if
		$d(a) < d(b)$	$d(a) = d(b)$	$d(a) > d(b)$
OR	$d(a \vee b)$	$d(a)$	$d(a)$	$d(b)$
AND	$d(a \wedge b)$	$d(b)$	$d(a)$	$d(a)$
NIBefore	$d(a \triangleleft b)$	$d(a)$	$+\infty$	$+\infty$
SIMLT	$d(a \triangle b)$	$+\infty$	$d(a)$	$+\infty$
IBefore	$d(a \trianglelefteq b)$	$d(a)$	$d(a)$	$+\infty$

Figure 14 shows an example of a DFT extracted from [23]. It is a cardiac assist system (**HCAS**), which is divided in four modules: trigger, CPU unit, motor section, and pumps. The trigger is divided in two components, CS and SS. The failure of any CS or SS, triggers a CPU unit failure. The primary CPU (P) has a warm³ spare (B). The motor module fails if both M and MC fail. In order for the pumps unit to fail, all three pumps need to fail, and the left-hand side spare gate needs to fail before (or at the same time as) the right-hand side spare gate (PAND gate⁴). The top-level event structure expression is:

$$\begin{aligned} SYSTEM = & CS \vee SS \vee (M \wedge MC) \vee & (3.4) \\ & (P \wedge (B_d \triangleleft P)) \vee (B_a \wedge (P \triangleleft B_a)) \vee \\ & (BP_a \wedge (P2 \triangleleft P1) \wedge (P1 \triangleleft BP_a)) \vee (P2 \wedge (P1 \triangleleft BP_a) \wedge (BP_a \triangleleft P2)) \end{aligned}$$

3.2 Structure expression analysis

In this section we explain the difference of stateful and stateless methods to analyse structure expressions and detail the stateless methods. A common approach to analyse an FT is to perform structure expression analysis based on algebraic laws. Boolean laws

³ Warm spare gates only differ from CSp on the activation time.

⁴ Although the original example uses a PAND gate, accordingly to the informal description, a SEQ gate would fit better.

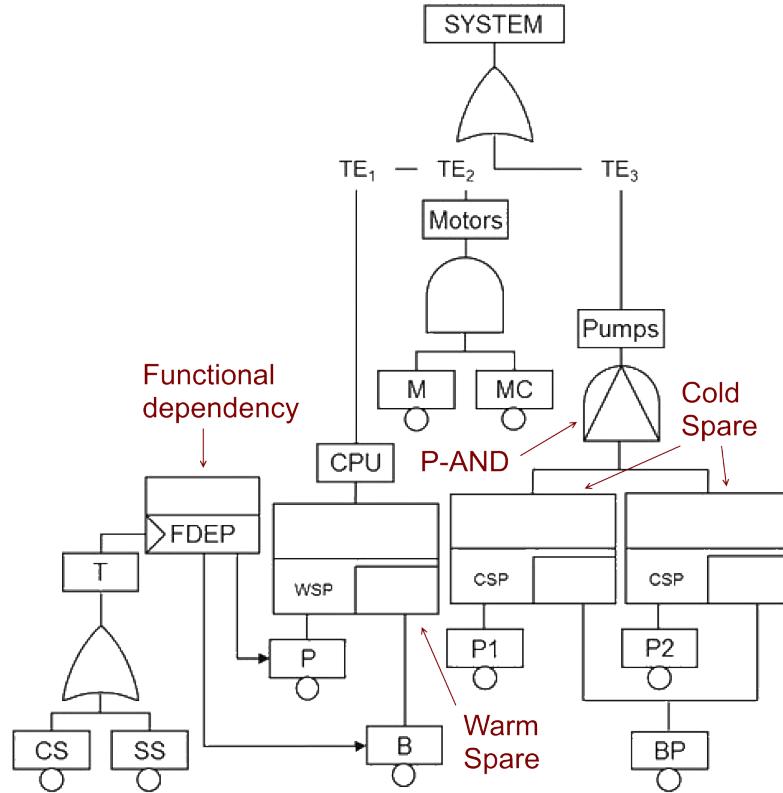


Figure 14 – DFT example

are well-known and are used for **SFTs**, temporal laws [21, 33] for **TFTs**, and the works reported in [3, 22] show laws for **DFTs**. An issue with algebraic laws is that, in some cases, the expression needs to be expanded before it gets rewritten. So, automation with rewriting is not trivial. For example, the following **TFT**'s structure expression needs to be expanded [33] before it gets reduced via rewriting:

$$\begin{aligned}
 & (X \wedge Y) \vee ((X < Y) \wedge Z) \\
 & = (X < Y) \vee (X \& Y) \vee (Y < X) \vee ((X < Y) \wedge Z) && \text{by Eq. (3.2a)} \\
 & = (X < Y) \vee (X \& Y) \vee (Y < X) && \text{by Boolean absorption of } X < Y \\
 & = X \wedge Y && \text{by Eq. (3.2a)}
 \end{aligned}$$

A denotational semantics to Boolean expressions—and consequently to **SFT**—is given by **FBA**s (Section 3.3). Using denotational semantics in favour of axiomatic laws is preferred as the axioms must be very simple or must be generally accepted, because a subtlety in an axiom (an unfounded axiom) may invalidate a whole theory.

There are several works with stateful analysis methods for **FTs** (**SFT**, **TFT**, and **DFT**). We show some of them in Subsection 3.2.1.

3.2.1 Stateful methods and temporal logic analysis

The work reported in [71] shows a formal approach to analyse **SFT** using Interval Temporal Logic (**ITL**) [72]. Instead of tackling basic events ordering (as in **PAND**), it considers a causal relation over a gate, as for example, a relation of a basic event and a higher-level intermediary event.

For **TFTs**, the works reported in [73, 74] show an inverse solution. They map Finite State Machines (**FSMs**) to Pandora logic, then verify system properties. They show that such a mapping simplifies expression reduction, thus improving performance on the analysis.

Although there is formal modelling approaches to **DFTs**, they do not implement a direct modelling of the **DFT** itself. Instead, most of the works propose a formal modelling using a state-based approach. The work reported in [35] shows a formal model of **Markov chains** in the Z Notation (**Z**) [75] and each **DFT** element (basic events and gates). The analysis uses a quantifier on states of the resulting **Markov chain** automaton. The work reported in [76] shows a methodology to perform a modular analysis of **DFTs** based on **BDD** and **Markov chain**. As **DFT** extends **SFT**, it identifies subtrees that are purely **SFT** and uses **BDD**, otherwise. It performs **Markov chain** analysis. Still on the state-based approaches, the work reported in [77] maps **DFTs** to high-level Petri-net (**HLPN**) [78] to analyse false alarms.

In the following we show specific stateless methods that are designed to reduce structure expressions. In essence, the methods are very similar. Structure expressions for **SFTs** can be reduced using **BDDs** (Subsection 3.2.2), **TFTs** can be reduced using **DTs** (Subsection 3.2.3), **MCSeqs** of **DFTs** can be obtained using Zero-suppressed Binary Decision Diagram (**ZBDD**) [65] (Subsection 3.2.4), and the works reported in [42, 43] show the analysis of standby systems (**CSp** gates) using **SBDDs** (Subsection 3.2.5).

3.2.2 Binary Decision Diagrams



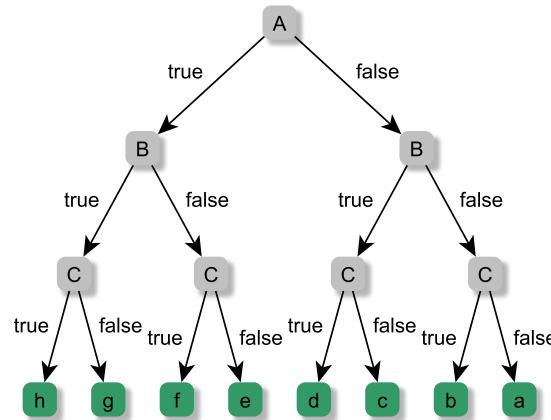
BDDs are directed acyclic graphs that represent a Boolean expression. They are still referred to as **BDD**, but the widespread version is the Reduced Ordered Binary Decision Diagram (**ROBDD**) [79], which is an optimisation. There are two ways to generate a **BDD** for an expression: (i) derive a diagram from the truth-table, or (ii) expand the paths based on Shannon's method (described in the Fault Tree Handbook).

To demonstrate the expressiveness of a **BDD**, Figure 15 shows a diagram for a truth table with three variables (Table 6). In a node, when a path is chosen, the variable of the node assumes the edge value. For example, the top-level node variable of Figure 15 is *A*. Following the right-hand side of the node, all leaf nodes correspond to the lines of the truth table that *A* has “0” values (the first four lines). The symbol nodes are replaced

Table 6 – Truth table for a formula outputs with three variables (A, B, and C)

A	B	C	Formula
0	0	0	a
0	0	1	b
0	1	0	c
0	1	1	d
1	0	0	e
1	0	1	f
1	1	0	g
1	1	1	h

by the values assumed by a specific formula.

**Figure 15** – A diagram for a truth table

Following Shannon's method, we choose a variable and build the lower level **BDD** assuming the edge value for the chosen variable. In the remainder of the path, the variable's value is unchanged. For example, the expression $A \vee (\neg B \wedge C)$ has value "0" in the lines *a* and *c*, and value "1" in the other lines. By choosing the variable *A* first, then *B* and *C*, the resulting **BDD** with the binary values nodes (called sink nodes "false" and "true") for this formula is depicted in Figure 16. Starting from the top-level node *A*, the formula expressed by the **BDD** is true if *A* assumes value true. If *A* is false, and *B* is false, the expression is only true if *C* is true.

Figure 16 is an **ROBDD**. To be considered an **ROBDD**, the **BDD** must meet the following constraints [79]:

- a) the variables are assigned a constant ordering;
- b) every path to sink nodes visit the input variables in ascending order;
- c) each node represents a distinct logic function.

For a given expression, the size of **BDDs** and **ROBDDs** depends on the chosen variables ordering. The work reported in [80] shows initial findings on best variable ordering, and

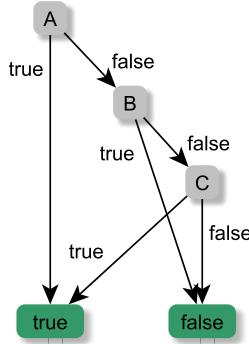


Figure 16 – A BDD for the expression $A \vee (\neg B \wedge C)$

the work reported in [81] shows heuristics to improve the performance for optimal order search.

For SFTs the evaluation of a BDD is the calculation of the probability of the paths ending in *true*. For example, the probability of the expression in Figure 16 is obtained from the formula: $\Pr\{A \vee (\neg A \wedge \neg B \wedge C)\}$. Note that the formula in the probability calculation is different from the formula that originated the diagram.

3.2.3 Dependency tree

Dependency tree (DT) [33] is a hierarchical acyclic graph of expressions that shows all possible cut sequences for any given set of events. It is a graphical view of a TTT. At the top of a DT are the variables, that is, the single events that occur in an expression. On the lower levels are the increasingly complex expressions. Each node represents an MCSeq. Figure 17 shows a DT with all nodes for variables X and Y .

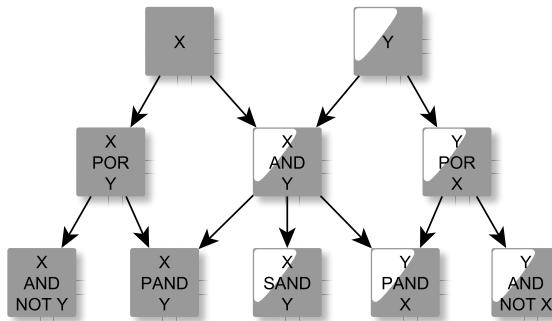


Figure 17 – DT for variables X and Y

The reduction of a structure expression is given by the activation (true values) of nodes. If a node is active (true), then all child nodes are also active; the converse is also true: if all node's children are active, then it is also active. The reduced expression is given by the DNF created with the expressions of higher active level nodes. To reduce the formula $(X \wedge Y) \vee ((X < Y) \wedge Z)$, given on the beginning of this subsection, we create the

DT depicted in Figure 18. Nodes marked with “1” are those MCSeqs given directly by the formula. Nodes marked with “2” are child nodes of the “1”’s nodes, and so forth. The node of the expression $((X < Y) \wedge Z)$ is a grandchild of $X \wedge Y$ and thus it is not necessary. The final expression is obtained by the active higher level node, which is $X \wedge Y$.

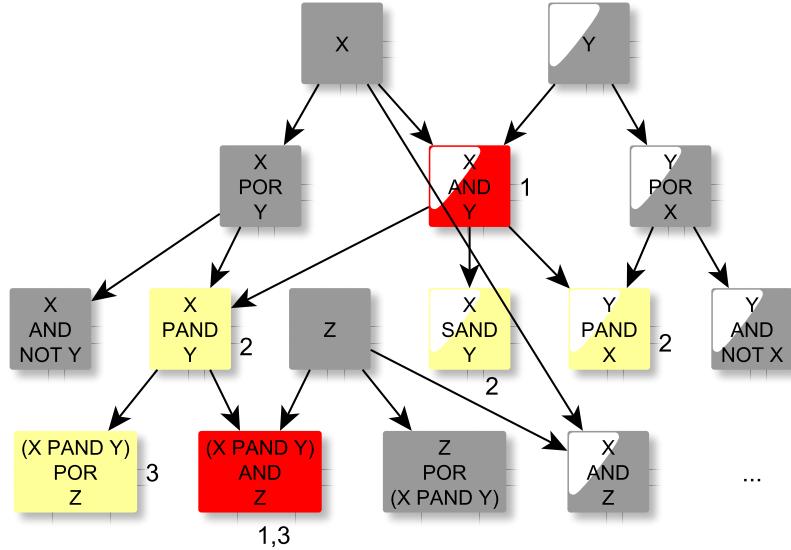


Figure 18 – DT for the formula $(X \wedge Y) \vee ((X < Y) \wedge Z)$

3.2.4 Zero-suppressed Binary Decision Diagrams

The work reported in [65] proposes Zero-suppressed Binary Decision Diagrams, which is a variant of BDD, and uses set manipulations (union, intersection, difference, and product) to obtain MCSeqs of DFTs.

To reduce a BDD to a ZBDD, the nodes that have the “true” (‘1’) path pointing to the “false” (‘0’) sink node are removed, and the parent node is connected directly to the “false” subgraph of the removed node. Figure 19 shows an example of ZBDD for the combination set $\{a, b\}$, as shown in [65]. The idea of the reduction is to remove irrelevant variables and nodes. The irrelevant variables are set to “false”. The method described in [65] obtains the MCSeqs by navigating the paths to sink node “true”.

Although the work reported in [65] shows ZBDD, the final solution does not use them directly. The idea is to transform the DFT into an SFT, in a very similar way as the one shown in [42]. The order-related operators in a DFT are replaced by a new event, which takes ordering into account. Finally, the MCSeqs are obtained using set manipulation with elements that are basic events alone or order-related operators. These order-related operators are event-to-event only, so they cannot be combined with other sets.

The use of sets in [65] is very related to our ATF. We use sets of sequences to define the ATF, but keep the analysis with set operators. In ATF we do not create new

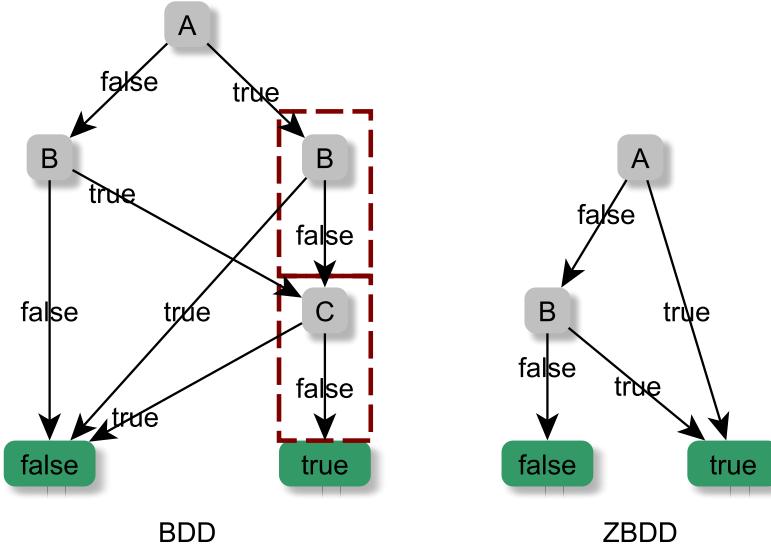


Figure 19 – ZBDD example of combination set $\{a, b\}$

events that represent an order-related operator. Our order-related operator has a set-based semantics that can be combined with other non-order-related (Boolean) operators.

3.2.5 Sequential Binary Decision Diagrams

SBDD is an extension of BDD to tackle ordering of events in DFTs for CSp and WSp gates. Ordering of events in CSp gates [43] is slightly different from WSp [42]. A backup system in CSp gets activated slower than in WSp, which implies that there are less failure possibilities in CSp, but its the readiness is lower than in WSp. SBDD adds a new kind of node that contains a binary operation of fault events, which allows to express the ordering of events. One kind of operation expresses the slowness of the relation of the fault events of CSp, and another one expresses the readiness of the WSp. The latter semantics is similar to the semantics of PAND and IBefore (combined with AND) gates.

SBDD creation has two steps: (i) CSp or WSp DFT conversion, and (ii) SBDD model generation. In (i), it is a DFT-to-DFT conversion. CSp and WSp gates are converted to a new, but equivalent DFT without CSp and WSp gates, where the operations appear as basic events and are combined using other gates. In (ii), the SBDD model is created. The model may contain nodes that are contradictory as, for example, nodes that assumes that an event A is false and a binary operation with AND semantics that contains A is true. This step ends when all contradictions are removed. The evaluation is similar to BDD's: each path ending in true is a minimal term in the DNF that may contain one of the binary operations and individual events.

3.3 Free Boolean Algebras

Another means to analyse SFTs is to use an FBA to perform set-theoretical operations (intersection, difference, etc.) to reduce expressions. In this section we briefly present the FBA theory and its elements.

Instead of using an axiomatic definition of a Boolean algebra directly, we follow its set-theoretical definition, as shown in [82, pp. 254–258] and [16, pp. 8–11]. This definition represents a Boolean algebra as an algebra of sets and does not rely on Boolean axioms (which can be misleading, if an unfounded axiom is present).

Definition 3.1 (Boolean Algebra). *A Boolean algebra is defined as a triple $\langle B, \cap, - \rangle$, where B is a set with at least two elements, \cap is the intersection (also called meet or infimum) and $-$ is the complement (also called negation).*

The other Boolean elements (union, \perp , and \top) are derived from the previous two operators:

\cup is the union (also called join or supremum): $A \cup B = -(-A \cap -B)$

\perp is the bottom (also called zero): $\perp = A \cap -A$

\top is the top (also called unit): $\top = -\perp$

A Free Boolean Algebra is defined from a set E of generators. A generator can be represented as a proposition in statement calculus [82, p. 274]. For example, “valve A is stuck closed” and “motor M is malfunctioning” are valid statements. A Free Boolean Algebra is constructed from $\mathbb{P}(E)$, where \mathbb{P} is the power set operator. Note that if E has n symbols, $\mathbb{P}(E)$ has 2^n elements, called *atoms* of a finite Boolean algebra. For the two statements above, the atoms are:

- a) “Valve A is stuck closed” and “motor X is malfunctioning”
- b) “Valve A is stuck closed” and “motor X is *not* malfunctioning”
- c) “Valve A is *not* stuck closed” and “motor X is malfunctioning”
- d) “Valve A is *not* stuck closed” and “motor X is *not* malfunctioning”

Such a Boolean algebra has 2^{2^n} formulas [16, p. 261]. For example, if $E = \{a, b\}$, then $\mathbb{P}(E) = \{\{\}, \{a\}, \{b\}, \{a, b\}\}$. And the Boolean algebra generated by E contains sixteen (2^{2^2}) formulas: $\{\}, \{\{\}\}, \{\{\}, \{a\}\}, \{\{\}, \{b\}\}, \dots, \{\{a\}, \{a, b\}\}, \dots, \{\{b\}, \{a, b\}\}, \dots, \{\{\}, \{a\}, \{b\}, \{a, b\}\}$.

The Boolean algebra B can be inductively defined using some constructs.

Definition 3.2 (Inductive Free Boolean Algebra). *Let s be a statement, then:*

$$\mathbf{var} s = \{X \mid s \in X\} \implies \mathbf{var} s \in B \quad (\text{variable}) \quad (3.5a)$$

$$X \in B \implies \neg X \in B \quad (\text{complement}) \quad (3.5b)$$

$$X \in B \wedge Y \in B \implies X \cap Y \in B \quad (\text{intersection}) \quad (3.5c)$$

The characterisation of a “free” Boolean algebra comes from that, for some valuation function a , some formulas evaluate to “1”. Given a function $p : B \times \{0, 1\} \rightarrow B$, such that:

$$p(i, j) = \begin{cases} i & j = 1 \\ -i & j = 0 \end{cases} \quad (3.6)$$

Lemma 3.1 (Free generators (valuation)). *Let F be a finite set, and E be a set of generators of a Boolean algebra, such that $F \subseteq E$, and $a : F \rightarrow \{0, 1\}$, a necessary and sufficient condition for the set E to be free is then:*

$$\bigwedge_{i \in F} p(i, a(i)) \neq 0 \quad (3.7)$$

Essentially, Lemma 3.1 states that there is no relation between generators, such as $a = -b$.

Lemma 3.2 (Free generators (algebraic)). *Let i and j be statements, such that $i, j \in E$, hence from Definition 3.2 and Lemma 3.1 it is necessary and sufficient that:*

$$\mathbf{var} i = \mathbf{var} j \iff i = j \quad (3.8a)$$

$$\mathbf{var} i \neq -\mathbf{var} j \quad (3.8b)$$

$$-\mathbf{var} i \neq \mathbf{var} j \quad (3.8c)$$

3.4 Using the NOT operator in Static Fault Trees

Although the Fault Tree Handbook introduces several gates, the vast majority of SFT analyses would fit in FTs with only AND and OR gates (coherent FTs). Qualitative analysis requires the reduction of the structure expression of FTs and, when NOT gates are present (non-coherent FTs), such a reduction can cause the interpretation of failure expression to be misled [9, 11, 10, 12, 13]. The work reported in [11] shows three funny examples of this kind of problem, and the works reported in [9, 12] show how to solve it using BDDs. In the following we show: (i) the second example presented in [11], which highlights the problem when using NOT gates (Subsection 3.4.1), and (ii) the second example presented in [9], which defends the usefulness of NOT gates in a multitasking system (Subsection 3.4.2).

Negated events in a non-coherent analysis are in fact the working state of a component. The failure probability contribution of a negated basic event is close to 1. The problem with non-coherent FTs is that its analysis can cause impossible situations. The general formula to identify coherency is given in [9, 12] in terms of a structure function.

Definition 3.3 (FT Coherency). Let $\Phi(x) : B^n \rightarrow B^1$ be a binary function of a vector of binary variables, such that $x = [x_1, x_2, \dots, x_n]$, representing the states of n system's components.

A binary structure function $\Phi(x)$ is coherent if all the following hold:

- a) $\Phi(x)$ is monotonic (non-decreasing) in each variable;
- b) Each x_i is relevant, which means that $\Phi(x)[x_i/1] \neq \Phi(x)[x_i/0]$ for some vector x .

where $B^1 = \{0, 1\}$, $B^n = B^{n-1} \times B^1$, $x_i = 1$ implies that component i failed, and $\Phi(x) = 1$ implies the system failed. For $y = [y_1, y_2, \dots, y_n]$, monotonicity of Φ means that for all i , $x_i \geq y_i$ ($y_i = 1 \implies x_i = 1$), and for some i , $x_i > y_i$ ($x_i = 1$ and $y_i = 0$). Variable replacement ($[a/b]$) is as usual: $x[x_i/a] = [x_1, \dots, x_{i-1}, a, x_{i+1}, \dots, x_n]$

3.4.1 Non-coherent fault tree misleads

In this subsection we illustrate—with the second example detailed in [11]—how a non-coherent FT misleads.

A college student who wants to visit her mother in another city has two options: wake up early (x_3) and take a ride with a friend (x_1), or wake up late ($\neg x_3$) and take the metro (x_2). The top-event failure is “visit mother” with expression $S = (x_1 \wedge x_3) \vee (x_2 \wedge \neg x_3)$. Its fault tree is depicted in Figure 20. It is clear that the structure function is non-coherent in x_3 accordingly to Definition 3.3: $\Phi(1, 1, x_3)[x_3/1] = \Phi(1, 1, x_3)[x_3/0]$.

The problem with this tree is the interpretation of the qualitative results. One of the possibilities in this scenario is that the college student would take a ride AND take the metro ($x_1 \wedge x_2$). Quantitatively, the analysis of the probabilities shows that this result is not negligible, but its interpretation is impossible.

3.4.2 Usefulness of NOT gates in FTA

In this subsection we show the second example detailed in [9].

The gas detection system depicted in Figure 21 has two sensors D_1 and D_2 which are used to detect a leakage in a confined space. When a leakage is detected, these sensors send a signal to the logic control unit LU , which performs three tasks:

- a) shuts-down the main system (process isolation) by de-energizing relay R_1 ;
- b) informs the operator of the leakage by lamp and siren L ;

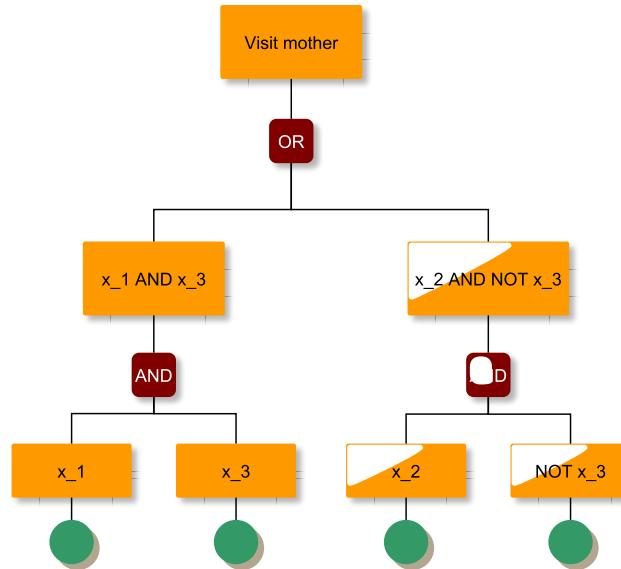


Figure 20 – Non-coherent FT college student’s example

- c) deactivates all possible ignition sources, which is the interruption of power supply by de-energizing relay R_2 .

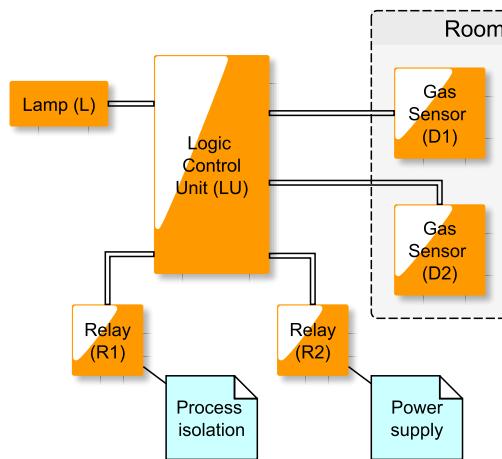


Figure 21 – Gas detection system

The system is in a fail state if it does not perform one of these three tasks. The fault tree that represents this generic failure is depicted in Figure 22. G_1 , G_2 , and G_3 are subtrees that represent the three tasks “Operator not informed”, “Process shut-down fails”, and “Power supply not isolated”, respectively. All three tasks will fail if their respective main component fails (L , R_1 , and R_2) or there is no signal from LU (LU fails or both D_1 and

D_2 fail). The structure expressions for the subtrees are:

$$G_1 = L \vee LU \vee (D_1 \wedge D_2)$$

$$G_2 = R_1 \vee LU \vee (D_1 \wedge D_2)$$

$$G_3 = R_2 \vee LU \vee (D_1 \wedge D_2)$$

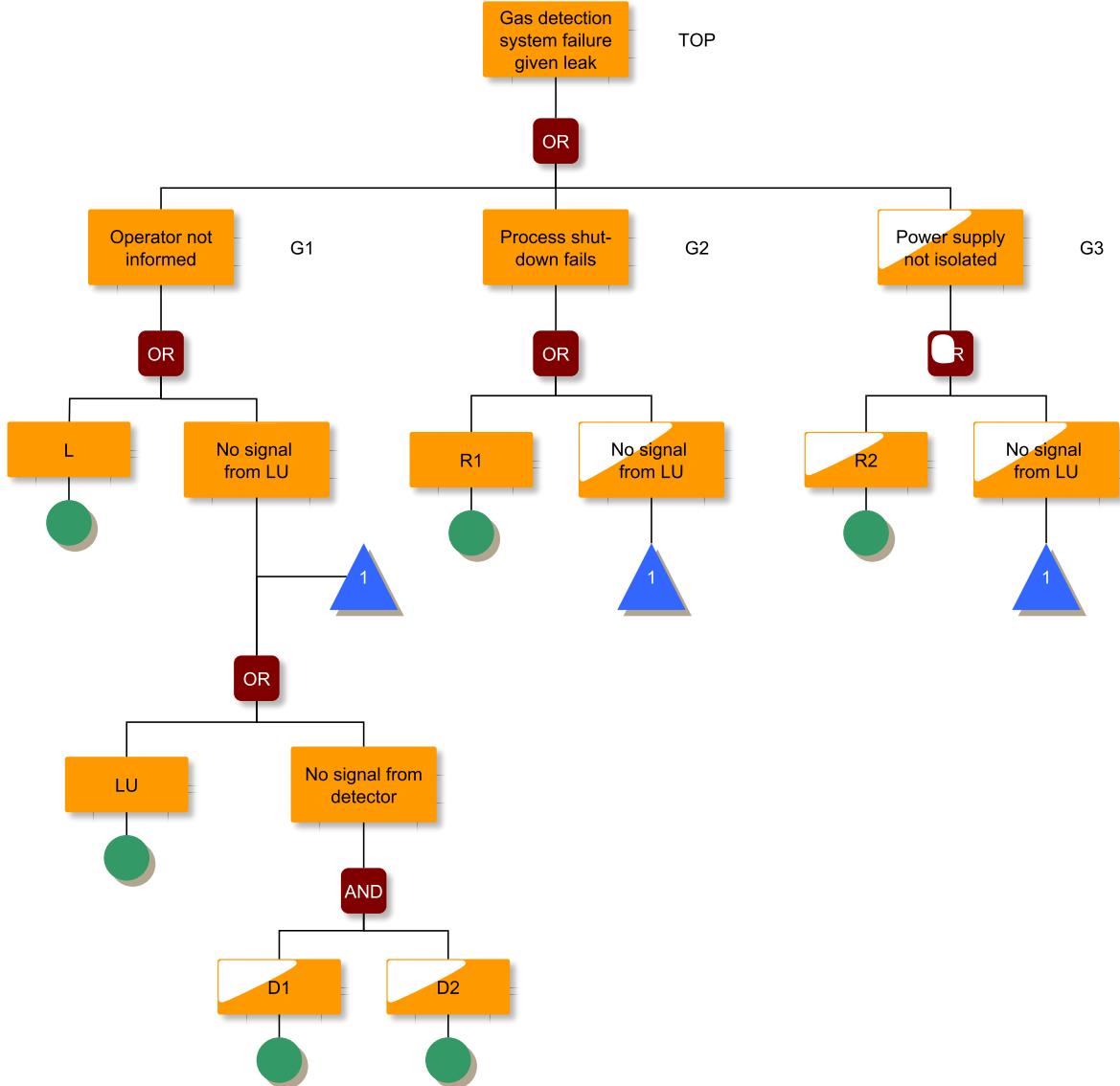


Figure 22 – FT for a generic failure in the gas detection system

Analysing in more detail, there are different degrees of system failure. There are eight outcomes (given the three tasks) and the most critical one is when both process shut-down (G_2) and power supply isolation (G_3) fail keeping energized upon a leakage, and the operator is not informed (G_1), but the operator information system is working (lamp and siren are off, but they are operational). The coherent FT of this outcome is depicted in Figure 23. The minimal cut sets obtained from this will be: $\{R_1, R_2\}$, $\{D_1, D_2\}$, and $\{LU\}$.

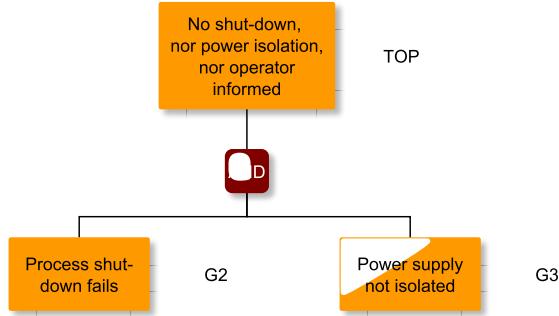


Figure 23 – Coherent FT for the most critical outcome of the gas detection system

Quantification of the coherent FT will overestimate the probability of the critical outcome unless the part of the system that is working (lamp and siren L , LU , and sensors D_1 and D_2) is taken into account. The non-coherent FT with the working part is shown in Figure 24.

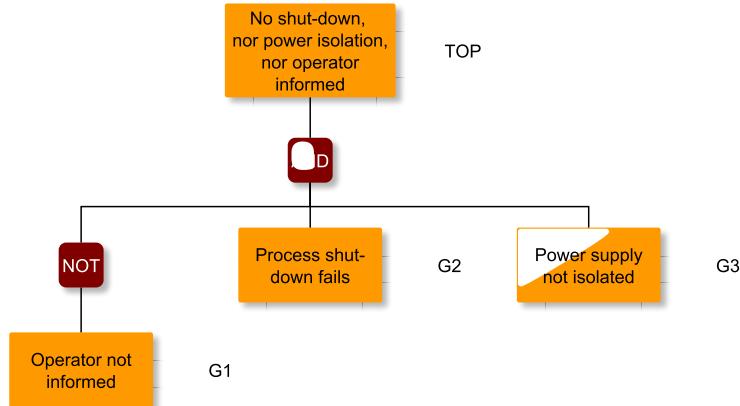


Figure 24 – Non-coherent FT for the most critical outcome of the gas detection system

If the operator *can* be informed, then cut sets $\{D_1, D_2\}$ and $\{LU\}$ could not have occurred (see Figure 22). Thus, the correct qualitative analysis should consider only cut set $\{R_1, R_2\}$. Reducing the expressions of the non-coherent FT (Figure 24), we obtain the structure expression: $\neg L \wedge \neg LU \wedge R_1 \wedge R_2 \wedge (\neg D_1 \vee \neg D_2)$. The approximation for this expression, removing the negated events, gives the cut set $\{R_1, R_2\}$, which gives a correct quantitative analysis.

3.4.3 Probabilistic analysis of a non-coherent tree

The work reported in [9] shows an example of an FT with an explicit NOT operator, the importance of such an operator, and how to calculate the probability of a critical failure. The system is a leak protection system that has valves and sensors, and is depicted

in Figure 25. Valve VAL closes a gas flow if a sensor detects a leak L . If the valve is closed for a certain amount of time, the pressure on the system may increase, and then, a relief valve PRV diverts the gas flow elsewhere.

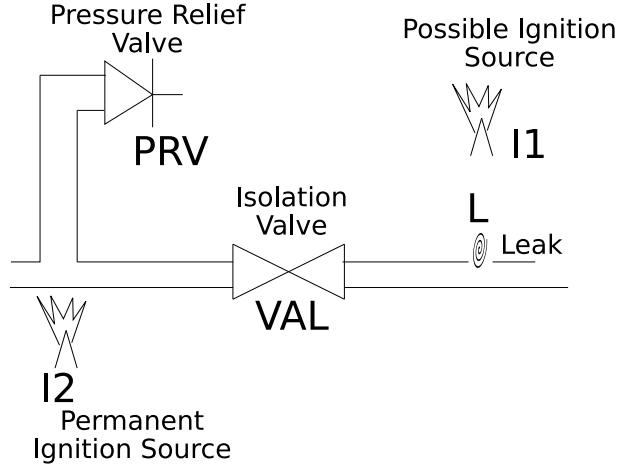


Figure 25 – Leak Protection System architectural view

The undesired top-event is an ignition in room 1 (TOP). As shown in [9], the structure expression of TOP is:

$$TOP = L \wedge ((\neg VAL \wedge PRV) \vee (VAL \wedge I_1)) \quad (3.9)$$

For a coherent analysis, they use the consensus law to add a “missing” term. In this case, the missing term is $L \wedge PRV \wedge I_1$. This gives the final expression:

$$TOP = L \wedge ((\neg VAL \wedge PRV) \vee (VAL \wedge I_1) \vee (PRV \wedge I_1)) \quad (3.10)$$

Finally, the probability for Eq. (3.9) is:

$$\Pr \{TOP\} = P_L \times (P_{PRV} + P_{VAL} \times P_{I_1} - P_{PRV} \times P_{VAL}) \quad (3.11)$$

where P_x is the failure probability of x , $x \in \{L, PRV, VAL, I_1\}$.

3.5 Systems nominal model and fault injection to obtain structure expressions

In this section we show how to obtain structure expressions from nominal models. Nominal models are architectural models to represent the nominal behaviour (without failures) of a system. Faults can be injected into a nominal model to simulate erroneous behaviour and observe which combinations of faults cause an unwanted operational mode. The group of such combinations in a single expression is, in fact, the structure expression of the unwanted operational mode (an FT’s structure expression of the system).

Control system modelling using Simulink block diagrams [83] is recommended in [30] and have been used by our industrial partner. It is a complementary tool of Matlab [84]. In fact, it works as a graphical interface to Matlab. A Simulink model has blocks and connections between these blocks, named signals. Each block has inputs and outputs and an internal behaviour expressed by its mathematical formula, which defines a function of the inputs for each output. There are many predefined blocks in the tool. It is also possible to create new blocks or use subsystems that encapsulate other blocks. A simulation adds extra parameters to a block diagram, like elapsed time and time between states. The elapsed time of a simulation is an abstraction for the quantity of possible simulation states and the time between states is related to the lowest common denominator of the sample time. Some components define different sample times, depending on their mode of operation. Usually, the value for this property is set to *auto*, allowing Simulink to choose a proper value automatically.

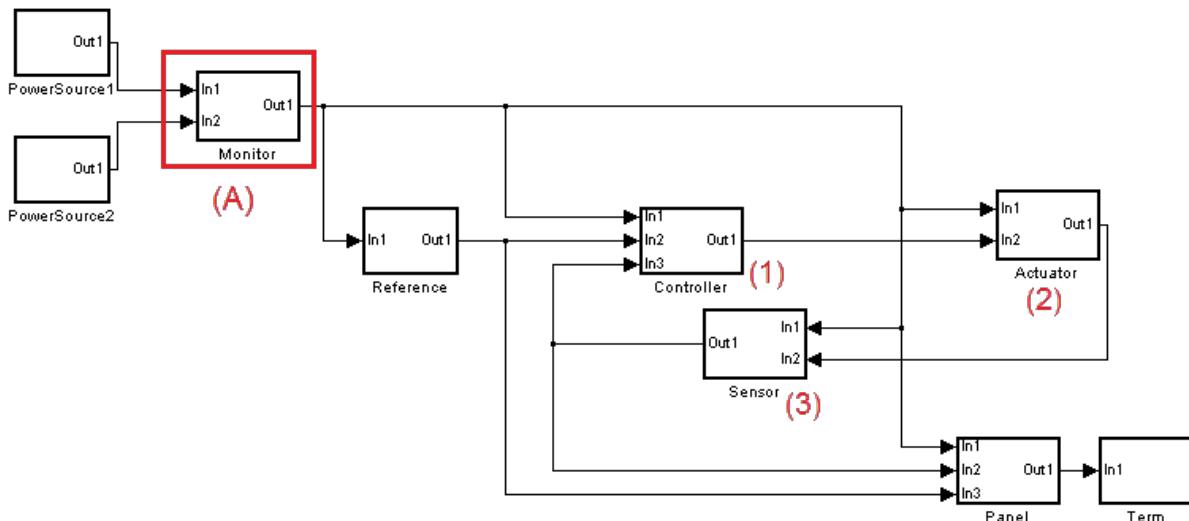


Figure 26 – Block diagram of the ACS provided by our industrial partner (nominal model)

Nowadays, control systems are usually composed of an electromechanical part and a processor. Figure 26 shows the components of a feedback system [85] which was provided by our industrial partner. In this system, the feedback behaviour is given by the *Controller* (1), *Actuator* (2) and *Sensor* (3). A command is received by the *Controller*, which sends a signal to the *Actuator* to start its movement. The *Sensor* detects the actual position of the *Actuator* and sends it back to the *Controller*, which adjusts the given command to achieve the desired position. This loop (feedback) continues until the desired position given by the original command is reached.

Figure 27 shows the internal elements of the monitor component (Figure 26 (A)), which is used as a case study in Chapter 6 to illustrate our strategy. The outputs of the hardware elements are annotated with *HW*, which are the two power sources and an

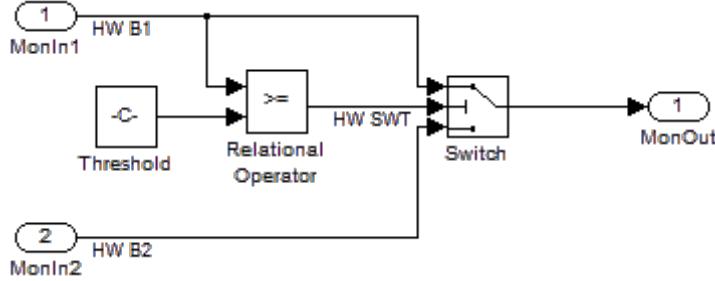


Figure 27 – Internal diagram of the monitor component (Figure 26 (A)).

internal component of the monitor (switch command).

To perform a formal verification in a Simulink system model we use the model-checking tool **FDR**. It is a refinement checker for formal models written in the formal language **CSP_M**. To verify a refinement⁵, it takes two specifications: (i) a specification with more abstract properties, and (ii) an implementation with more concrete properties. If a refinement does not hold (the implementation fails to refine the specification), **FDR** shows counter-examples as traces of events. The **CSP_M** language is suitable to model concurrent behaviour and is very expressive to model systems' states. The work reported in [31] translates a Simulink model to the **CSP_M** language. The resulting **CSP_M** code (implementation) is then used to check if it meets functional requirements also encoded in **CSP_M** (specification).

In our previous work, reported in [28], we modified such a translation to perform fault injection using hardware annotations allowing a subsystem or part to “break” randomly. We designed a **CSP_M** process to act as an observer (specification), watching outputs of the nominal version and comparing to the outputs of the “breakable” version (with injected faults—the implementation) of the system. When the **CSP_M** process of the model and the observer are loaded into the **FDR** model-checker, counter-examples are generated for each output that differs from the nominal model, thus obtaining a *sequence* of injected fault combinations that leads to the unexpected output, which are indeed *fault traces*.

In what follows, injected faults and the top-level failure have generic names based on the names of the Simulink model blocks. It is out of the scope of [28] to define event names.

For the Simulink model shown in Figure 27, some representative fault traces are:

```
TRACE 1:
failure.Hardware.N04_RelationalOperator.1.EXP.B.true
failure.Hardware.N04_RelationalOperator.1.ACT.B.false
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION
out.1.OMISSION
```

⁵ A refinement is an improvement in a specification. Such an improvement can be the reduction on the number of communications, bounding values or by a different representation of data.

TRACE 2:
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION
failure.Hardware.N04_RelationalOperator.1.EXP.B.true
failure.Hardware.N04_RelationalOperator.1.ACT.B.false
out.1.OMISSION

TRACE 3:
failure.Hardware.N04_MonIn1.1.EXP.I.5
failure.Hardware.N04_MonIn1.1.ACT.OMISSION
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION
out.1.OMISSION

TRACE 4:
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION
failure.Hardware.N04_MonIn1.1.EXP.I.5
failure.Hardware.N04_MonIn1.1.ACT.OMISSION
out.1.OMISSION

TRACE 5:
failure.Hardware.N04_MonIn1.1.EXP.I.5
failure.Hardware.N04_MonIn1.1.ACT.OMISSION
failure.Hardware.N04_RelationalOperator.1.EXP.B.false
failure.Hardware.N04_RelationalOperator.1.ACT.B.true
out.1.OMISSION

TRACE 6:
failure.Hardware.N04_MonIn1.1.EXP.I.5
failure.Hardware.N04_MonIn1.1.ACT.OMISSION
failure.Hardware.N04_RelationalOperator.1.EXP.B.false
failure.Hardware.N04_RelationalOperator.1.ACT.B.true
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION
out.1.OMISSION

TRACE 7:
failure.Hardware.N04_MonIn1.1.EXP.I.5
failure.Hardware.N04_MonIn1.1.ACT.OMISSION
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION
failure.Hardware.N04_RelationalOperator.1.EXP.B.false
failure.Hardware.N04_RelationalOperator.1.ACT.B.true

TRACE 8:
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION
failure.Hardware.N04_MonIn1.1.EXP.I.5
failure.Hardware.N04_MonIn1.1.ACT.OMISSION
failure.Hardware.N04_RelationalOperator.1.EXP.B.false
failure.Hardware.N04_RelationalOperator.1.ACT.B.true

TRACE 9:
failure.Hardware.N04_RelationalOperator.1.EXP.B.false
failure.Hardware.N04_RelationalOperator.1.ACT.B.true

```

failure.Hardware.N04_MonIn1.1.EXP.I.5
failure.Hardware.N04_MonIn1.1.ACT.OMISSION
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION

TRACE 10:
failure.Hardware.N04_RelationalOperator.1.EXP.B.false
failure.Hardware.N04_RelationalOperator.1.ACT.B.true
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION
failure.Hardware.N04_MonIn1.1.EXP.I.5
failure.Hardware.N04_MonIn1.1.ACT.OMISSION

TRACE 11:
failure.Hardware.N04_MonIn2.1.EXP.I.5
failure.Hardware.N04_MonIn2.1.ACT.OMISSION
failure.Hardware.N04_RelationalOperator.1.EXP.B.false
failure.Hardware.N04_RelationalOperator.1.ACT.B.true
failure.Hardware.N04_MonIn1.1.EXP.I.5
failure.Hardware.N04_MonIn1.1.ACT.OMISSION

```

where N04 is the subsystem name of the monitor in the Simulink diagram, MonIn1 (first input of the monitor), MonIn2 (second input of the monitor), and RelationalOperator (switcher controller) are the names of the hardware components in the Simulink diagram.

We only show eleven counter-examples, but FDR generates a total of 64 counter-examples for this system. The other counter-examples are similar to the traces shown with different internal events.

To reuse HiP-HOPS, which is based on SFTs, we “remove” the ordering information of the traces to generate a failure expression. Each fault trace is abstracted as a conjunction (**AND** combination of the inner events, thus losing the ordering information), and the several conjunction-based fault events are combined using **ORs** (disjunctions). The result of the combination is a Boolean expression that represents the conditions that cause an undesirable output, the failure expression of the model. With the ATF proposed in this work we do not “remove” the ordering information, so we are able to use this information to generate or perform DFT and TFT analyses (TFTs have order-related operators, and it is shown in [3, 24, 22] that DFTs can be expressed by order-related operators).

If the failure expression is obtained for a whole system, it is indeed the structure expression of a fault tree for a general failure as the top-level event. Although it is possible to obtain the failure expression for a larger system, it may be impractical due to state-space explosion in CSP_M model analysis. Thus it should be used for components and subsystems or small systems following HiP-HOPS compositional structure. Using failure expression as subsystem annotations in [25], it is possible to obtain structure expressions for a larger system. It is worth noting that the goal of the work reported in [28] was to connect with HiP-HOPS, which is based on static fault trees. But we already knew that we had a

richer fault modelling information than that presented in [28] because we abstracted traces (which already capture fault events ordering) to create propositions (any fault events order combination).

To show how these traces become failure expression, let us abbreviate fault names as:

```
A = failure.Hardware.N04_MonIn1.1
B = failure.Hardware.N04_MonIn2.1
S = failure.Hardware.N04_RelationalOperator
```

So, for each trace, we obtain an expression:

```
TRACE 1 = S ∧ B
TRACE 2 = B ∧ S
TRACE 3 = A ∧ B
TRACE 4 = B ∧ A
TRACE 5 = A ∧ S
TRACE 6 = A ∧ S ∧ B
TRACE 7 = A ∧ B ∧ S
TRACE 8 = B ∧ A ∧ S
TRACE 9 = S ∧ A ∧ B
TRACE 10 = S ∧ B ∧ A
TRACE 11 = B ∧ S ∧ A
```

And we combine them as a single Boolean expression: $\text{TRACE 1} \vee \text{TRACE 2} \vee \text{TRACE 3} \vee \text{TRACE 4} \vee \text{TRACE 5} \vee \text{TRACE 6} \vee \text{TRACE 7} \vee \text{TRACE 8} \vee \text{TRACE 9} \vee \text{TRACE 10} \vee \text{TRACE 11}$, which by a traditional Boolean reduction strategy results in:

$$(A \wedge B) \vee (S \wedge (A \vee B))$$

The above expression is exactly the same failure expression provided by our industrial partner if we use the following association (Table 7):

```
A = LowPower-In1
B = LowPower-In2
S = SwitchFailure
```

Table 7 – Annotations table of the ACS provided by our industrial partner

Component	Deviation	Port	Annotation
PowerSource	LowPower	Out1	PowerSourceFailure
Monitor	LowPower	Out1	(SwitchFailure AND (LowPower-In1 OR LowPower-In2)) OR (LowPower-In1 AND LowPower-In2)
Reference	OmissionSignal	Out1	ReferenceDeviceFailure OR LowPower-In1

Note that when we combine each fault with **AND** gates, we lose the information about order⁶: $S \wedge B$ and $B \wedge S$ are equal, due to the commutative law of Boolean expressions.

Our strategy finds fault combinations S and B (in the sense of S occurring before B) as well as B and S (in the sense of B occurring before S) but abstracts this ordering information obtaining B and S , which is equivalent to S and B in Boolean Algebra. If A fails before S , the system fails because it should switch to B , but the switcher is in a faulty state. On the other hand, if S fails before A , the switcher fails because it inadvertently switched to B when A was still operational. When A fails, nothing changes and the output of the system is obtained from B .

We also employed the strategy proposed in the work [28] in another case study and obtained a weaker failure expression (that is, our expression considers more cases). The failure expression provided by the engineers of our industrial partner was stronger because they considered that one component has a very low probability of failure and removed it from the analysis. Our strategy on the other hand generates the weakest failure expression; the best qualitative solution possible. Obviously that by quantitative analysis we can obtain the same structure expression as provided by the engineers of our industrial partner.

3.6 Isabelle/HOL

We use the same words of the creators of this tool, retrieved from their website⁷:

Isabelle is a generic proof assistant. It allows mathematical formulas to be expressed in a formal language and provides tools for proving those formulas in a logical calculus. The main application is the formalization of mathematical proofs and in particular formal verification, which includes proving the correctness of computer hardware or software and proving properties of computer languages and protocols.

⁶ In our previous work we designed the observer to ignore order as well, by making similar traces—with different ordering—the same size. Here we modified the observer specification to make similar traces with different sizes.

⁷ Accessed 27/jan/2016: <<https://isabelle.in.tum.de/overview.html>>

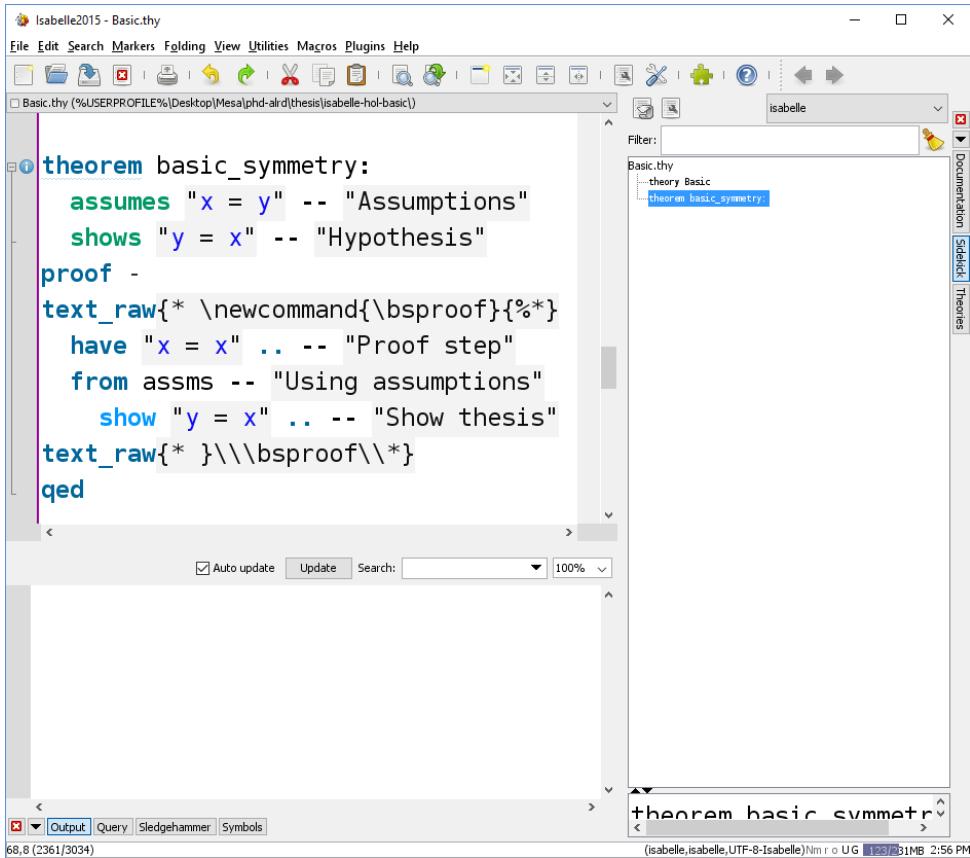


Figure 28 – Isabelle/HOL window, showing the basic symmetry theorem

Isabelle/HOL is the most widespread instance of Isabelle. **HOL** stands for higher-order logic. Isabelle/HOL provides a **HOL** proving environment ready to use, which includes: (co)datatypes, inductive definitions, recursive functions, locales, custom syntax definition, etc. Proofs can be written in both human⁸ and machine-readable language based on **Isar**. The tool also includes the *sledgehammer*, a port to call external first-order provers to find proofs fully automatically. The user interface is based on jEdit⁹, which provides a text editor, syntax parser, shortcuts, etc. (see Figure 28).

Theories on Isabelle/HOL are based on a few axioms. Isabelle/HOL Library's theories—which comes with the installer—and user's theories are based on these axioms. This design decision avoids inconsistencies and paradoxes (similar as it is in **Z**).

Besides the provided theories, its active community provides a comprehensive archive of formal proofs¹⁰ (**AFP**). Each entry in this archive can be cited and usually contains an *abstract*, a document, and a theory file. For example, a Free Boolean Algebra theory is available in [86]. To use it, it is enough to download and put on the same directory of your own theory files.

⁸ By human we mean that anyone with mathematics and logic basic knowledge—it means that deep programming knowledge is not essential.

⁹ Accessed 27/jan/2016: <<http://www.jedit.org/>>

¹⁰ Accessed 27/jan/2016: <<http://afp.sourceforge.net/>>

Bellow we show an example and explain the overall syntax of the human and machine-readable language.

```
theorem basic_symmetry:
  assumes "x = y" — Assumptions
  shows "y = x" — Hypothesis
proof -
  have "x = x" .. — Proof step
  from assms — Using assumptions
  show "y = x" .. — Show thesis
qed
```

Finally, Isabelle/HOL provides L^AT_EX syntax sugar and allow easy document preparation: this entire section was written in a theory file mixing Isabelle's and L^AT_EX's syntax). The above theorem can be written using Isabelle's quotation and anti-quotations. For example, we can write it using usual L^AT_EX theorem environment:

Theorem 3.1 (Basic symmetry). *Assuming $x = y$, thus:*

$$y = x$$

Proof. **have** "x = x" .. — Proof step

from assms — Using assumptions

show "y = x" .. — Show thesis

□

Otherwise specified, in the next sections we will omit proofs because they are all verified using Isabelle/HOL. The complete listing is in Appendix A.

4 A free algebra to express structure expressions of ordered events

Recall from Sections 2.2 and 3.1 that fault events are statistically independent of one another. The set-theoretical abstraction of structure expressions for SFTs [18, pp. VI-11] is very close to an FBA, where each generator in FBAs corresponds to a fault event symbol in fault trees. In FBAs, as generators are “free”, they are independent of one another and Boolean formulas are written as a set of sets of possibilities, which are similar to the structure expressions of SFTs.

We showed in Section 3.1 that there is a consistent presence of order-based operators to analyse TFTs and DFTs, and that each approach describes a new algebra based on different representations of events ordering with similar theorems to reduce expressions to a normal form.

From the need to tackle events ordering, related to the failure traces we can obtain by applying the fault injection strategy we developed in [28], we defined a list-based algebra, called Algebra of Temporal Faults (ATF), to express and analyse systems considering events ordering. We also provide a mapping from fault traces [28] (from CSP_M models) to this algebra, shown in Section 4.5. The order-specific operations are expressed with a new operator (\rightarrow) that we call exclusive-before (XBefore).

The set of sets for FBAs is our proposed denotational semantics for Boolean algebras. We use the concept of generators to propose the ATF with a denotational semantics of a set of lists without repetition (distinct lists¹). The choice for lists is because this structure inherently associates a generator to an index, making implicit the representation of order. These lists are composed of non-repeated elements (distinct lists) because the events in fault trees are non-repairable. Thus, they do not occur more than once.

The elements of a list have an implicit order number, but such an order number is different from the Sequence Number function used in [20, 21]. Although different, the order number in lists is related to the concept that there should be no gaps of the indexes between consecutive events occurrence. The structure of the lists ensures this restriction. But it is different because order 0 (zero) in [20, 21] means non-occurrence. It may cause a discontinuity because 0 to 1 is different of 1 to 2. In FBAs the non-occurrence of an event is just the absence of the event. Thus we use the same representation of non-occurrence as absence of the event in ATF to avoid this discontinuity. For example, the following lists are all permutations of fault events a and b (the generators are a and b):

¹ Although some may use the terminology “disjoint lists” to call the lists of non-repeated elements, we use the same terminology (distinct lists) of the theories built-in the Isabelle/HOL tool.

\emptyset : no fault occurs

$[a]$: fault a occurs and b does not

$[b]$: fault b occurs and a does not

$[a, b]$: fault a occurs before b . Note that, a has index 0 and b has index 1.

$[b, a]$: fault b occurs before a .

In the following we show the definitions and laws of our proposed **ATF**. To avoid repetition, let S , T and U be sets of distinct lists. A list xs is distinct if it has no repeated element. So, if x is in xs , then it has a unique associated index i and we denote it as $x = xs_i$, where $i \neq j$ and there is no xs_j such that $x = xs_j$. Furthermore, as we follow an **FBA** characterisation, we also need to show that the generators are independent.

The **ATF** form a free algebra similar to **FBA**s. *Infimum* and *Supremum* are denoted as set intersection (\cap) and union (\cup) respectively. The order within the algebra is defined as set inclusion (\subseteq).

To distinguish the permutations that are not defined in **FBA**, we need a new operator. We give the definition of **XBefore** (\rightarrow) in terms of list concatenation, similar to the work reported in [87]:

$$\llbracket S \rightarrow T \rrbracket = \{ zs \mid \exists xs, ys \bullet (\text{set } xs) \cap (\text{set } ys) = \{\} \wedge xs \in \llbracket S \rrbracket \wedge ys \in \llbracket T \rrbracket \wedge zs = xs @ ys \} \quad (4.1)$$

where the **set** function returns the set of the elements of a list, $@$ concatenates two lists, and $\llbracket . \rrbracket$ obtains the denotational semantics of the formula.

In some cases it is more intuitive to use the **XBefore** definition in terms of lists slicing because it uses indexes explicitly. Lists slicing is the operation of taking or dropping elements, obtaining a sublist. In slicing, the starting index is inclusive, and the ending one is exclusive. Thus the first index is 0 and the last index is the list length. For example, the list $xs_{[0..|xs|]}$ is equal to the xs list, where $|xs|$ is the list length. We use the following notation for list slicing:

$$xs_{[i..j]} = \text{starts at } i \text{ and ends at } j - 1 \quad (4.2a)$$

$$xs_{[..j]} = xs_{[0..j]} \quad (4.2b)$$

$$xs_{[i..]} = xs_{[i..|xs|]} \quad (4.2c)$$

To simplify the use of list slicing, its definition includes the lower and upper bounds as 0 and its length, respectively:

$$xs_{[i..j]} = xs_{[L..U]} \quad (4.3)$$

where $L = \max 0, i$ and $U = \min j, |xs|$.

List slicing and concatenation are complementary: concatenating two consecutive slices results in the original list:

$$\forall i \bullet xs_{[..i]} @ xs_{[i..]} = xs \quad (4.4)$$

There is an equivalent definition of **XBefore** with concatenation using lists slicing:

$$[S \rightarrow T] = \{ z_s \mid \exists i \bullet z_{s_{[..i]}} \in [S] \wedge z_{s_{[i..]}} \in [T] \} \quad (4.5)$$

A variable in **ATF** is defined by one generator, and denotes its occurrence:

$$[\mathbf{var} x] = \{ z_s \mid x \in z_s \} \quad (4.6)$$

where $\text{set } z_s$ is the set of the elements of z_s , and $x \in z_s$ is defined as $x \in \text{set } z_s$.

For example, for generators a and b , we obtain the following denotational semantics:

$$[\mathbf{var} a] = \{ [a], [a, b], [b, a] \} \quad (4.7a)$$

$$[\mathbf{var} b] = \{ [b], [a, b], [b, a] \} \quad (4.7b)$$

Given this definition, we show a small example on how the **XBefore** operator works:

For $z_s = []$, $[] \notin [\mathbf{var} a] \wedge [] \notin [\mathbf{var} b] \implies$

$$[] \notin [\mathbf{var} a \rightarrow \mathbf{var} b]$$

For $z_s = [a]$, $[a] \in [\mathbf{var} a] \wedge [a] \notin [\mathbf{var} b] \wedge [] \notin [\mathbf{var} b] \implies$

$$[a] \notin [\mathbf{var} a \rightarrow \mathbf{var} b]$$

For $z_s = [b]$, $[b] \in [\mathbf{var} b] \wedge [b] \notin [\mathbf{var} a] \wedge [] \notin [\mathbf{var} a] \implies$

$$[b] \notin [\mathbf{var} a \rightarrow \mathbf{var} b]$$

For $z_s = [a, b]$, $[a] \in [\mathbf{var} a] \wedge [b] \in [\mathbf{var} b] \implies$

$$[a, b] \in [\mathbf{var} a \rightarrow \mathbf{var} b]$$

For $z_s = [b, a]$, $[b] \notin [\mathbf{var} a] \wedge [] \notin [\mathbf{var} a] \wedge [b, a] \in [\mathbf{var} a] \wedge$

$$[] \notin [\mathbf{var} b] \wedge [a] \notin [\mathbf{var} b] \wedge [b, a] \in [\mathbf{var} b] \implies$$

$$[b, a] \notin [\mathbf{var} a \rightarrow \mathbf{var} b]$$

$$[\mathbf{var} a \rightarrow \mathbf{var} b] = \{ [a, b] \} \quad (4.8)$$

Boolean operators are denoted as in **FBA**:

$$\llbracket S \wedge T \rrbracket = \llbracket S \rrbracket \cap \llbracket T \rrbracket \quad (4.9a)$$

$$\llbracket S \vee T \rrbracket = \llbracket S \rrbracket \cup \llbracket T \rrbracket \quad (4.9b)$$

$$\llbracket \neg S \rrbracket = \text{UNIV} - \llbracket S \rrbracket \quad (4.9c)$$

$$\llbracket \perp \rrbracket = \{ \} \quad (4.9d)$$

$$\llbracket \top \rrbracket = \text{UNIV} \quad (4.9e)$$

UNIV is the universal set. It contains all permutations of the generators of size 0 to the number of the generators. We denote the set of generators $\text{Gen}(S)$ of a formula S as:

$$\text{Gen}(S) = \bigcup_{xs \in \llbracket S \rrbracket} \text{set } xs \quad (4.10)$$

The generators of **ATF** are $\text{Gen}(\text{UNIV})$, or simply Gen . For example, if the generators are a and b , then **UNIV** is:

$$\{ \[], [a], [b], [a, b], [b, a] \}$$

The following expressions are sufficient to define the **ATF** in terms of an inductively defined set (**atf**):

$$\llbracket \text{var } x \rrbracket \in \text{atf} \quad \text{Variable} \quad (4.11a)$$

$$\llbracket S \rrbracket \in \text{atf} \implies \llbracket \neg S \rrbracket \in \text{atf} \quad \text{Complement, Negation} \quad (4.11b)$$

$$\llbracket S \rrbracket \in \text{atf} \wedge \llbracket T \rrbracket \in \text{atf} \implies \llbracket S \wedge T \rrbracket \in \text{atf} \quad \text{Intersection, Infimum} \quad (4.11c)$$

$$\llbracket S \rrbracket \in \text{atf} \wedge \llbracket T \rrbracket \in \text{atf} \implies \llbracket S \rightarrow T \rrbracket \in \text{atf} \quad \text{XBefore} \quad (4.11d)$$

Following these definitions, the expressions below are also valid for **atf**:

$$\text{UNIV} \in \text{atf} \quad \text{Universal set, True} \quad (4.11e)$$

$$\{ \} \in \text{atf} \quad \text{Empty set, False} \quad (4.11f)$$

$$\llbracket S \rrbracket \in \text{atf} \wedge \llbracket T \rrbracket \in \text{atf} \implies \llbracket S \vee T \rrbracket \in \text{atf} \quad \text{Union, Supremum} \quad (4.11g)$$

The **NOT** operator is given in terms of **UNIV**. For example, for generators a and b :

$$\begin{aligned} \llbracket \neg \text{var } a \rrbracket &= \text{UNIV} - \llbracket \text{var } a \rrbracket && \text{by Eq. (4.9c)} \\ &= \{[], [a], [b], [a, b], [b, a]\} - \{[a], [a, b], [b, a]\} && \text{by Eq. (4.7a)} \\ &= \{[], [b]\} \end{aligned} \quad (4.12)$$

To avoid repetition, we abbreviate Eq. (4.9c) suppressing **UNIV**. For example:

$$\text{UNIV} - A \equiv -A$$

The following expressions are valid for generators a and b and are sufficient to show that the generators are independent:

$$\llbracket \mathbf{var} a \rrbracket = \llbracket \mathbf{var} b \rrbracket \iff a = b \quad (4.13a)$$

$$\llbracket \mathbf{var} a \rrbracket \not\subseteq -\llbracket \mathbf{var} b \rrbracket \quad (4.13b)$$

$$\llbracket \mathbf{var} a \rrbracket \neq -\llbracket \mathbf{var} b \rrbracket \quad (4.13c)$$

$$-\llbracket \mathbf{var} a \rrbracket \not\subseteq \llbracket \mathbf{var} b \rrbracket \quad (4.13d)$$

$$-\llbracket \mathbf{var} a \rrbracket \neq \llbracket \mathbf{var} b \rrbracket \quad (4.13e)$$

Expressions Eq. (4.11a) to Eq. (4.11g) and Eq. (4.13a) to Eq. (4.13e) implies that the **ATF** without the **XBefore** operator Eq. (4.1) forms a Boolean algebra based on sets of lists. And this is also equivalent to an **FBA** with the same generators.

In our previous work [87] we stated a relation between **XBefore** and *supremum*, provided the operands are variables Eq. (4.6). Now we generalise this relation in terms of abstract properties of the operands of the **XBefore**. We name these properties as *temporal properties*.

4.1 Temporal properties (*tempo*)

Temporal properties give a more abstract and less restrictive shape on the **XBefore** laws. They are abbreviations that some operators satisfy altogether or individually.

The first temporal property is about disjoint split. If the first part of a list is in a given set, then every remainder part is not. So, if a generator is in the beginning of a list, it must not be at the end (and vice-versa).

$$\mathbf{tempo}_1 S = \forall i, j, zs \bullet i \leq j \implies \neg(zs_{[..i]} \in \llbracket S \rrbracket \wedge zs_{[j..]} \in \llbracket S \rrbracket) \quad (4.14)$$

For example, let $zs = [z_0, z_1, z_2, z_3, z_4]$. If $[z_0, z_1] \in \llbracket S \rrbracket$, thus $[z_3, z_4] \notin \llbracket S \rrbracket$. Note that it is vague, but it is the first relation indication on the lists of S . In this property, as zs has no repeated elements, then there is no element that is in both sublists.

In what follows we show how variables satisfy **tempo** properties. To avoid repetition, the denotational semantics of **var** z_1 is considered for generators z_1, z_2, z_3 :

$$\begin{aligned} \llbracket \mathbf{var} z_1 \rrbracket = & \{[z_1], [z_1, z_2], [z_2, z_1], [z_1, z_3], [z_3, z_1], [z_1, z_2, z_3], [z_1, z_3, z_2], \\ & [z_2, z_1, z_3], [z_2, z_3, z_1], [z_3, z_1, z_2], [z_3, z_2, z_1]\} \end{aligned} \quad (4.15)$$

We demonstrate that the property **tempo₁** is satisfied:

$$\begin{aligned}
 [z_1] \in \llbracket S \rrbracket &\implies [z_2] \notin \llbracket S \rrbracket \wedge [z_3] \notin \llbracket S \rrbracket \wedge [z_2, z_3] \notin \llbracket S \rrbracket \wedge [z_3, z_2] \notin \llbracket S \rrbracket \\
 [z_1, z_2] \in \llbracket S \rrbracket &\implies [z_3] \notin \llbracket S \rrbracket \\
 [z_2, z_1] \in \llbracket S \rrbracket &\implies [z_3] \notin \llbracket S \rrbracket \\
 [z_1, z_3] \in \llbracket S \rrbracket &\implies [z_2] \notin \llbracket S \rrbracket \\
 [z_3, z_1] \in \llbracket S \rrbracket &\implies [z_2] \notin \llbracket S \rrbracket \\
 [z_1, z_2, z_3] \in \llbracket S \rrbracket &\implies [] \notin \llbracket S \rrbracket \\
 &\dots
 \end{aligned}$$

The second temporal property is about belonging to one sublist in the beginning or in the end:

$$\mathbf{tempo}_2 S = \forall i, z_s \bullet z_s \in \llbracket S \rrbracket \iff z_{s[..i]} \in \llbracket S \rrbracket \vee z_{s[i..]} \in \llbracket S \rrbracket \quad (4.16)$$

For example, if a generator is in a list, then it must be in a prefix or in a suffix. If $[z_0, z_1, z_2, z_3, z_4] \in \llbracket S \rrbracket$, thus either $[z_0] \in \llbracket S \rrbracket$, or $[z_1, z_2, z_3, z_4] \in \llbracket S \rrbracket$. If $[z_0] \notin \llbracket S \rrbracket$, thus $[z_1, z_2, z_3, z_4] \in \llbracket S \rrbracket$. Then, either $[z_1] \in \llbracket S \rrbracket$ or $[z_2, z_3, z_4] \in \llbracket S \rrbracket$, and so forth. For variable **var** z_1 :

$$\begin{aligned}
 [z_1] \in \llbracket S \rrbracket &\iff [z_1] \in \llbracket S \rrbracket \vee [] \in \llbracket S \rrbracket \\
 [z_1, z_2] \in \llbracket S \rrbracket &\iff [z_1] \in \llbracket S \rrbracket \vee [z_2] \in \llbracket S \rrbracket \\
 [z_1, z_2, z_3] \in \llbracket S \rrbracket &\iff ([z_1] \in \llbracket S \rrbracket \vee [z_2, z_3] \in \llbracket S \rrbracket) \wedge \\
 &\quad ([z_1, z_2] \in \llbracket S \rrbracket \vee [z_3] \in \llbracket S \rrbracket) \\
 [z_2, z_1, z_3] \in \llbracket S \rrbracket &\iff ([z_2] \in \llbracket S \rrbracket \vee [z_1, z_3] \in \llbracket S \rrbracket) \wedge \\
 &\quad ([z_2, z_1] \in \llbracket S \rrbracket \vee [z_3] \in \llbracket S \rrbracket) \\
 &\dots
 \end{aligned}$$

The third temporal property is about belonging to one sublist in the middle. If a generator belongs to a sublist between j and i , then it belongs to the sublist that starts at the first position and ends in the j^{th} and to the sublist that starts at i^{th} and ends at the last position (both sublists contain the sublist in the middle).

$$\begin{aligned}
 \mathbf{tempo}_3 S = \forall i, j, z_s \bullet j < i &\implies \\
 (z_{s[j..i]} \in \llbracket S \rrbracket \iff z_{s[..i]} \in \llbracket S \rrbracket \wedge z_{s[j..]} \in \llbracket S \rrbracket) &\quad (4.17)
 \end{aligned}$$

For example, if $[z_1, z_2, z_3] \in \llbracket S \rrbracket$, then both $[z_0, z_1, z_2, z_3] \in \llbracket S \rrbracket$ and $[z_1, z_2, z_3, z_4] \in \llbracket S \rrbracket$.

For a variable **var** z_1 :

$$\begin{aligned}
 [z_1] \in \llbracket S \rrbracket &\iff [z_1] \in \llbracket S \rrbracket \wedge [z_1] \in \llbracket S \rrbracket \wedge \\
 &\quad [z_2, z_1] \in \llbracket S \rrbracket \wedge [z_1] \in \llbracket S \rrbracket \wedge \\
 &\quad [z_3, z_1] \in \llbracket S \rrbracket \wedge [z_1] \in \llbracket S \rrbracket \wedge \\
 &\quad [z_1] \in \llbracket S \rrbracket \wedge [z_1, z_2] \in \llbracket S \rrbracket \wedge \\
 &\quad [z_1] \in \llbracket S \rrbracket \wedge [z_1, z_3] \in \llbracket S \rrbracket \wedge \\
 &\quad [z_2, z_1] \in \llbracket S \rrbracket \wedge [z_1, z_3] \in \llbracket S \rrbracket \wedge \\
 &\quad [z_3, z_1] \in \llbracket S \rrbracket \wedge [z_1, z_2] \in \llbracket S \rrbracket \\
 [z_1, z_2] \in \llbracket S \rrbracket &\iff [z_3, z_1, z_2] \in \llbracket S \rrbracket \wedge [z_1, z_2] \in \llbracket S \rrbracket \\
 &\quad [z_1, z_2] \in \llbracket S \rrbracket \wedge [z_1, z_2, z_3] \in \llbracket S \rrbracket \\
 &\quad \dots
 \end{aligned}$$

Finally, if a generator belongs to a list, then there is a sublist of size one that contains the generator.

$$\mathbf{tempo}_4 S = \forall z s \bullet z s \in \llbracket S \rrbracket \iff (\exists i \bullet z s_{[i..(i+1)]} \in \llbracket S \rrbracket) \quad (4.18)$$

If list $zs = [z_0, z_1, z_2, z_3, z_4] \in \llbracket S \rrbracket$, then one list $[z_i] \in \llbracket S \rrbracket$, where $i \in \{0, \dots, 4\}$. For a variable **var** z_1 :

$$\begin{aligned}
 [z_1] \in \llbracket S \rrbracket &\iff [z_1] \in \llbracket S \rrbracket \\
 [z_1, z_2] \in \llbracket S \rrbracket &\iff [z_1] \in \llbracket S \rrbracket \vee [z_2] \in \llbracket S \rrbracket \\
 [z_1, z_2, z_3] \in \llbracket S \rrbracket &\iff [z_1] \in \llbracket S \rrbracket \vee [z_2] \in \llbracket S \rrbracket \vee [z_3] \in \llbracket S \rrbracket \\
 &\quad \dots
 \end{aligned}$$

In general, for any generator z , the following is valid:

$$\mathbf{tempo}_1(\mathbf{var} z) \wedge \mathbf{tempo}_2(\mathbf{var} z) \wedge \mathbf{tempo}_3(\mathbf{var} z) \wedge \mathbf{tempo}_4(\mathbf{var} z) \quad (4.19)$$

We abbreviate Eq. (4.19) as:

$$\mathbf{tempo}_{1-4} S = \mathbf{tempo}_1 S \wedge \mathbf{tempo}_2 S \wedge \mathbf{tempo}_3 S \wedge \mathbf{tempo}_4 S \quad (4.20)$$

In our previous work [87] we used set difference to specify the **XBefore** operator. Provided $\mathbf{tempo}_1 S$ and $\mathbf{tempo}_1 T$, **XBefore** in [87] is equivalent to Eq. (4.1):

$$\begin{aligned}
 \llbracket S \rightarrow T \rrbracket = \{zs \mid \exists xs, ys \bullet xs \in \llbracket S \rrbracket - \llbracket T \rrbracket \wedge ys \in \llbracket T \rrbracket - \llbracket S \rrbracket \wedge \\
 \text{distinct } zs \wedge zs = xs @ ys\}
 \end{aligned} \quad (4.21)$$

Other expressions also meet one or more temporal properties:

$$\text{tempo}_1 S \wedge \text{tempo}_1 T \implies \text{tempo}_1(S \wedge T) \quad (4.22\text{a})$$

$$\text{tempo}_3 S \wedge \text{tempo}_3 T \implies \text{tempo}_3(S \wedge T) \quad (4.22\text{b})$$

$$\text{tempo}_2 S \wedge \text{tempo}_2 T \implies \text{tempo}_2(S \vee T) \quad (4.22\text{c})$$

$$\text{tempo}_4 S \wedge \text{tempo}_4 T \implies \text{tempo}_4(S \vee T) \quad (4.22\text{d})$$

4.2 XBefore laws

We now show some laws to be used in the algebraic reduction of **ATF** formulas. The laws follow from the definition of **XBefore**, from events independence, and from the temporal properties.

We use a normal form similar to the **DNF** of Boolean algebra. In **DNF** each sub-expression is a minimal cut set for **SFT**. In our normal form, also called **DNF**, we allow **ANDs**, **NOTs**, and **XBefores** to be in the sub-expressions. Each sub-expression is a set of minimal cut sequences for **TFT** and **DFT**. The following formulas are in **DNF**:

$$\begin{aligned} & (A \wedge \neg B \wedge \neg C) \vee ((A \rightarrow B) \rightarrow C) \\ & A \rightarrow B \\ & A \rightarrow B \rightarrow C \end{aligned}$$

The following formulas are *not* in **DNF**:

$$\begin{aligned} & A \vee B \\ & A \wedge B \\ & \neg(A \vee B) \\ & A \wedge (B \vee C) \\ & A \rightarrow (B \vee C) \\ & A \rightarrow (B \wedge C) \end{aligned}$$

But to transform the last two formulas into **DNF**, one can use Eqs. (4.27a) to (4.27d), for instance. The **DNF** is clearer with the mapping function from denotational semantics to a formula formula (.) presented in Section 4.3.

We define events independence (\Leftrightarrow) as the property that one operand does not imply the other. For example, in some rules we need to avoid that the operands of **XBefore** are **var** a and **var** $a \vee \text{var } b$ (it results in $\{\}$, see Eq. (4.24g)).

$$S \Leftrightarrow T = \forall i, z_s \bullet \neg(zs_{[i..(i+1)]} \in \llbracket S \rrbracket \wedge zs_{[i..(i+1)]} \in \llbracket T \rrbracket) \quad (4.23)$$

For generators a and b and the denotational semantics of $\mathbf{var} a$ and $\mathbf{var} b$ (see Eqs. (4.7a) and (4.7b)), it is easy to check that $\mathbf{var} a \Leftrightarrow \mathbf{var} b$ is satisfied, and $\mathbf{var} a \Leftrightarrow (\mathbf{var} a \vee \mathbf{var} b)$ is not. Essentially if the formulas contain independent events one must not imply on the other on the occurrence of individual events ($zs_{[i..(i+1)]}$).

The absence of occurrences ($\{\}$, the empty set of **atf**) is a “0” for the **XBefore** operator. The negation of all events ($\{\}\}$, a formula with the empty list) is a “1” for the **XBefore** operator.

$$\perp \rightarrow S = \perp \quad (4.24a)$$

$$S \rightarrow \perp = \perp \quad (4.24b)$$

$$\mathbf{tempo}_1 S \implies 1 \rightarrow S = S \quad (4.24c)$$

$$\mathbf{tempo}_1 S \implies S \rightarrow 1 = S \quad (4.24d)$$

$$(S \rightarrow T) \vee S = S \quad (4.24e)$$

$$(T \rightarrow S) \vee S = S \quad (4.24f)$$

$$\mathbf{tempo}_1 S \implies S \rightarrow S = \perp \quad (4.24g)$$

$$\begin{aligned} \mathbf{tempo}_1 S \wedge \mathbf{tempo}_1 T \wedge \mathbf{tempo}_1 U &\implies \\ S \rightarrow (T \rightarrow U) &= (S \rightarrow T) \rightarrow U \end{aligned} \quad (4.24h)$$

The **XBefore** is absorbed by one of the operands: if one of the operands may happen alone, thus the order with any other operand is irrelevant. However, an event cannot come before itself, thus **XBefore** is not idempotent. The **XBefore** is associative.

To allow formula reduction we need the relation of **XBefore** to the other Boolean operators. First we use the **XBefore** as operands of **OR** and **AND**.

$$\begin{aligned} \mathbf{tempo}_1 S \wedge \mathbf{tempo}_1 T &\implies \\ (S \rightarrow T) \wedge (T \rightarrow S) &= \perp \end{aligned} \quad (4.25a)$$

$$\begin{aligned} \mathbf{tempo}_{1-4} S \wedge \mathbf{tempo}_{1-4} T \wedge S \Leftrightarrow T &\implies \\ (S \rightarrow T) \vee (T \rightarrow S) &= S \wedge T \end{aligned} \quad (4.25b)$$

As **XBefore** is not symmetric, the intersection of symmetrical **XBefore**s is empty. The **OR** of symmetrical **XBefore**s is a partition of the intersection of the operands. For example, given generators a and b ($a \neq b$):

$$(\mathbf{var} a \rightarrow \mathbf{var} b) \vee (\mathbf{var} b \rightarrow \mathbf{var} a) = \mathbf{var} a \wedge \mathbf{var} b \quad (4.26)$$

because $\mathbf{var} a$ and $\mathbf{var} b$ satisfy all temporal properties (Eq. (4.19)) and are independent events.

In our previous work [87], we stated that S and T had to be variables, for example, of the form $\mathbf{var} s$ and $\mathbf{var} t$. Now, each law requires that the operands satisfy some of the temporal properties, avoiding using variables explicitly.

Expressions with Boolean operators are used as operands of the **XBefore** in the following laws.

$$(S \vee T) \rightarrow U = (S \rightarrow U) \vee (T \rightarrow U) \quad (4.27a)$$

$$S \rightarrow (T \vee U) = (S \rightarrow T) \vee (S \rightarrow U) \quad (4.27b)$$

$$\begin{aligned} \mathbf{tempo}_{1-4} S \wedge \mathbf{tempo}_{1-4} T \wedge S \Leftrightarrow T &\implies \\ (S \wedge T) \rightarrow U &= (S \rightarrow T \rightarrow U) \vee \\ (T \rightarrow S \rightarrow U) \end{aligned} \quad (4.27c)$$

$$\begin{aligned} \mathbf{tempo}_{1-4} T \wedge \mathbf{tempo}_{1-4} U \wedge T \Leftrightarrow U &\implies \\ S \rightarrow (T \wedge U) &= (S \rightarrow T \rightarrow U) \vee \\ (S \rightarrow U \rightarrow T) \end{aligned} \quad (4.27d)$$

$$\begin{aligned} \mathbf{tempo}_2 S &\implies S \wedge (T \rightarrow U) = ((S \wedge T) \rightarrow U) \vee \\ (T \rightarrow (S \wedge U)) \end{aligned} \quad (4.27e)$$

$$\begin{aligned} \mathbf{tempo}_1 T \wedge \mathbf{tempo}_3 T &\implies \\ S \rightarrow T \wedge T \rightarrow U &= (S \rightarrow T) \rightarrow U \end{aligned} \quad (4.27f)$$

$$\begin{aligned} S \Leftrightarrow T \wedge \mathbf{tempo}_{1-4} S \wedge \mathbf{tempo}_{1-4} T &\implies \\ S \wedge (S \rightarrow T) &= S \rightarrow T \end{aligned} \quad (4.27g)$$

$$\begin{aligned} S \Leftrightarrow T \wedge \mathbf{tempo}_{1-4} S \wedge \mathbf{tempo}_{1-4} T &\implies \\ S \wedge (T \rightarrow S) &= T \rightarrow S \end{aligned} \quad (4.27h)$$

XBefore is distributive over **OR**. On the other hand, the **AND** is not. The **AND** of an event with an **XBefore** states that such an event can occur in any order within the events in the **XBefore**. Lastly, the **XBefore** is transitive with preconditions over the intermediary variable.

The law name, unordered, of Eq. (4.27e) is clearer if we expand Eq. (4.27e) with Eq. (4.27c) and Eq. (4.27d):

$$\begin{aligned} \mathbf{tempo}_{1-4} S \wedge \mathbf{tempo}_{1-4} T \wedge \\ \mathbf{tempo}_{1-4} U \wedge S \Leftrightarrow T \wedge S \Leftrightarrow U &\implies \\ S \wedge (T \rightarrow U) &= (S \rightarrow T \rightarrow U) \vee \\ (T \rightarrow S \rightarrow U) \vee \\ (T \rightarrow U \rightarrow S) &\quad \text{expanded-unordered} \quad (4.28) \end{aligned}$$

In what follows we show properties of **XBefore** related to the **NOT** operators.

$$\begin{aligned} S \Leftrightarrow T \wedge \mathbf{tempo}_{1-4} S \wedge \mathbf{tempo}_{1-4} T \implies \\ \neg(S \rightarrow T) = (\neg S \vee \neg T) \vee (T \rightarrow S) \end{aligned} \quad (4.29a)$$

$$\begin{aligned} \mathbf{tempo}_1 S \wedge \mathbf{tempo}_2 T \implies \\ \neg S \rightarrow T = T \end{aligned} \quad (4.29b)$$

$$\begin{aligned} \mathbf{tempo}_1 T \wedge \mathbf{tempo}_2 S \implies \\ S \rightarrow \neg T = S \end{aligned} \quad (4.29c)$$

$$\begin{aligned} S \Leftrightarrow T \wedge \mathbf{tempo}_{1-4} S \wedge \mathbf{tempo}_{1-4} T \implies \\ (S \wedge \neg T) \vee (S \rightarrow T) = S \wedge \neg(T \rightarrow S) \end{aligned} \quad (4.29d)$$

4.3 Soundness and completeness

We use type classes in Isabelle/HOL to describe the language (operators, also called *parameters*) and the axioms (*assumptions*) of **ATF**. Following our proposed denotational semantics, the instantiation of the type class maps each operator to a set of distinct lists, including the operators of Boolean algebra and the **XBefore** operator. Such an instantiation requires proof obligations for the type (the set of distinct lists), which we discharged. With all proofs, Isabelle/HOL asserts that the declared type (the set of sets of distinct lists) is indeed an **ATF**². For example, Eq. (4.25b) is defined in **ATF** and is proved mapping each syntactical element to the denotational semantics (the set of distinct lists). Moreover, all Eqs. (4.24e), (4.24f), (4.27c), (4.27d), (4.27g), (4.27h), (4.28) and (4.29d) are theorems proved syntactically and inherited by the instantiation for set of sets of distinct lists. Soundness of the instantiation with respect to the type class assumptions is a direct consequence of such an instantiation.

To illustrate this built-in property, consider Eq. (4.25b). The following formula can be proved directly in Isabelle/HOL using term rewriting only:

$$\begin{aligned} \mathbf{var} a \rightarrow \mathbf{var} b \vee \mathbf{var} b \rightarrow \mathbf{var} a \vee \neg(\mathbf{var} a \wedge \mathbf{var} b) \\ = (\mathbf{var} a \wedge \mathbf{var} b) \vee \neg(\mathbf{var} a \wedge \mathbf{var} b) \quad \text{by Eq. (4.25b)} \\ = \top \quad \text{by Boolean law} \end{aligned}$$

Thus, the type class of **ATF** is able to show that:

$$\llbracket \mathbf{var} a \rightarrow \mathbf{var} b \vee \mathbf{var} b \rightarrow \mathbf{var} a \vee \neg(\mathbf{var} a \wedge \mathbf{var} b) \rrbracket = \text{UNIV}$$

and also:

$$\llbracket \mathbf{var} a \rightarrow \mathbf{var} b \vee \mathbf{var} b \rightarrow \mathbf{var} a \rrbracket = \llbracket \mathbf{var} a \wedge \mathbf{var} b \rrbracket$$

² Technically, we split the laws in smaller classes and prove them separately—starting with Boolean algebra—composing all classes later.

where UNIV is the set of all distinct lists.

All the above formulas are theorems on the semantics, but are proved using the assumptions declared on the type class hierarchy (Boolean and [ATF](#)).

To prove soundness explicitly (without relying on type classes), we declare a datatype:

```
datatype 'a formula_syntax =
  sFalse |
  sVar 'a |
  sNot 'a formula_syntax |
  sAnd 'a formula_syntax 'a formula_syntax |
  sXB 'a formula_syntax 'a formula_syntax
```

The semantics of a `formula_syntax` is similar to what we show in this chapter:

$$\begin{aligned} \llbracket \text{sFalse} \rrbracket &= \perp \\ \llbracket \text{sVar } a \rrbracket &= \text{var } a \\ \llbracket \text{sNot } f \rrbracket &= - \llbracket f \rrbracket \\ \llbracket \text{sAnd } f_1 \ f_2 \rrbracket &= \llbracket f_1 \rrbracket \wedge \llbracket f_2 \rrbracket \\ \llbracket \text{sXB } f_1 \ f_2 \rrbracket &= \llbracket f_1 \rrbracket \rightarrow \llbracket f_2 \rrbracket \end{aligned}$$

Note that we mapped the semantics of a formula to the operators of Boolean algebra and [ATF](#). This is possible due to the locales and contexts in Isabelle/HOL. Type classes use both structures of locales and contexts, thus it allows to reuse the operators for sets of distinct lists, as we show above.

Proposition 4.1 (Soundness). *Let f be a formula in [ATF](#) and Σ be a set of simplification rules of the syntax, then:*

$$\forall f \bullet \Sigma \vdash f \implies \Sigma \models f \tag{4.30}$$

The syntactical application of the rules can be defined in Isabelle/HOL as an inductive definition. Thus, if a formula is in such an inductive definition, then such a formula is provable. We have not defined yet inductive definition for provable. On the semantics side (right hand side of Eq. (4.30)) we use the mapping function above, which have been proved for sets of distinct lists.

The semantic completeness is the converse of soundness: if a formula has the semantics of \top , then such a formula is provable (syntactically) for the set of rules Σ .

Proposition 4.2 (Completeness). *Let f be a formula in [ATF](#) and Σ be a set of simplification rules of the syntax, then:*

$$\forall f \bullet \Sigma \models f \implies \Sigma \vdash f \tag{4.31}$$

4.4 Qualitative and quantitative analyses

In Section 3.1 we showed the kind of results that are obtained in FTA. In this section we show how to formalize these FTA results as: (i) MCSeq, the number of fault elements in the minimal sequences that cause a root failure, and (ii) the root probability, given the availability of basic fault occurrences probabilities. These attributes of an FT are the most representative ones, but other can be modelled similarly.

4.4.1 Minimal cut sequence

Recall from the beginning of this chapter that the denotational semantics of ATF is a set of distinct lists. Thus, each list has no repeated elements and represent a possible combination of faults that causes the root failure. MCSeqs are those distinct lists with the least length, defined in what follows.

Definition 4.1 (Minimal cut sequences). *Let S be a formula in ATF. Its minimal cut sequences (MCSeq of S) are:*

$$\text{MCSeq}(S) = \{ xs \mid xs \in \llbracket S \rrbracket \bullet |xs| = \min_S \} \quad (4.32)$$

where

$$\min_S = \text{Min}(\{ |xs| \mid xs \in \llbracket S \rrbracket \})$$

and Min returns the least sequence length in the given set.

For example, the MCSeqs of $\text{var } a \rightarrow (\text{var } b \vee \text{var } c)$ (for generators a , b , and c) are:

$$\text{MCSeq}(\text{var } a \rightarrow (\text{var } b \vee \text{var } c)) = \{ [a, b], [a, c] \} \quad (4.33)$$

Equation (4.33) states that it is sufficient that a occurs before b , or a occurs before c , to cause the top event. Other lists in the denotational semantics of the formula are $[a, b, c]$ and $[a, c, b]$, but these are not minimal.

4.4.2 Root probability



The work reported in [3] shows how to calculate the probability of a PAND gate as:

$$\begin{aligned} P(t) &= \Pr\{T_1 \leq T_2\}^{<t} \\ &= \int_0^t P'_2(t_2) \int_0^{t_2} P'_1(t_1) dt_1 dt_2 \\ &= \int_0^t P'_2(t_2) P_1(t_2) dt_2 \end{aligned} \quad (4.34)$$

where P_1 and P_2 are the probabilities of the occurrences of the first and the second faults (cumulative distribution function), respectively, and T_1 and T_2 are the times the first and the second faults occur. The general case (reported in [88]) of a PAND gate with n inputs is the probability of the sequence of faults f_i , $i \in \{1, \dots, n\}$:

$$\Pr \{[f_1, f_2, \dots, f_{n-1}, f_n]\} = \int_0^t P'_n(t_n) \int_0^{t_n} P'_{n-1}(t_{n-1}) \dots \int_0^{t_3} P'_2(t_2) \int_0^{t_2} P'_1(t_1) dt_1 dt_2 \dots dt_{n-1} dt_n \quad (4.35)$$

where P_i is the cumulative probability function of fault f_i .

For ATF, our proposal for probability calculation is defined in terms of the probability of PAND gates. The reason is that our semantics is defined in terms of a set of lists (or sequences) of fault occurrences. The main difference from the PAND calculation as reported in [88] is that repeated situations must be removed. For example, the probability of $\llbracket \text{var } f_1 \rightarrow \text{var } f_2 \rrbracket$ contains the situations in which f_1 occurs before f_2 and f_3 does not occur, or f_3 occurs in some time: $\Pr \{[f_1, f_2, f_3]\}$, $\Pr \{[f_1, f_3, f_2]\}$, and $\Pr \{[f_3, f_1, f_2]\}$.

Using Eqs. (4.10) and (4.35) we define the probability for a fault sequence as:

$$\Pr_{\text{FS}} \{xs\} = \Pr \{xs\} \times \prod_{f_j \in \text{Gen-set } xs} (1 - P_j(t)) \quad (4.36)$$

For example, for generators f_1 , f_2 , and f_3 , $\Pr_{\text{FS}} \{[f_1, f_2]\} = \Pr \{[f_1, f_2]\} \times (1 - P_3(t))$, which is the probability of f_1 occurring before f_2 and f_3 not occurring.

As the probability of each fault sequence is independent of each other, the probability of an ATF formula is the sum of the denotational probabilities of its constituent lists.

Definition 4.2 (Probability of a formula in ATF). *Let S be a formula in ATF. Then the probability of S , $\text{FPr}\{S\}$, is given by:*

$$\text{FPr}\{S\} = \sum_{xs \in \llbracket S \rrbracket} \Pr_{\text{FS}} \{xs\} \quad (4.37)$$

The interesting part behind the probabilistic calculus over the denotational semantics is that it is only about ordering of events. It means that even if a formula contains a NOT operator, we still safely obtain a probability value, without worrying about complement probabilities as tackled in [9]. For example, the denotational semantics of $\neg \text{var } f_1$ (for generators f_1 and f_2) is:

$$\begin{aligned} \llbracket \neg \text{var } f_1 \rrbracket &= \text{UNIV} - \llbracket \text{var } f_1 \rrbracket \\ &= \text{UNIV} - \{[f_1], [f_1, f_2], [f_2, f_1]\} \\ &= \{[], [f_1], [f_2], [f_1, f_2], [f_2, f_1]\} - \{[f_1], [f_1, f_2], [f_2, f_1]\} \\ &= \{[], [f_2]\} \end{aligned} \quad (4.38)$$

and the probability of $\neg \text{var } f_1$ is:

$$\begin{aligned}
\text{FPr}\{\neg \text{var } f_1\} &= \text{Pr}_{\text{FS}}\{\emptyset\} + \text{Pr}_{\text{FS}}\{[f_2]\} && \text{by Eq. (4.37)} \\
&= \text{Pr}\{\emptyset\} \times (1 - P_1(t)) \times (1 - P_2(t)) \\
&\quad + \text{Pr}\{[f_2]\} \times (1 - P_1(t)) && \text{by Eq. (4.36)} \\
&= 1 \times (1 - P_1(t)) \times (1 - P_2(t)) \\
&\quad + P_2(t) \times (1 - P_1(t)) && \text{by Eq. (4.35)} \\
&= 1 - P_1(t)
\end{aligned} \tag{4.39}$$

The empty list is a special case and has value 1. It works as the universal complement probability of any other list. When the empty list appears in a denotational semantics it means that the top-event occurs if no fault occurs.

We use the traditional probability calculations [3] as reference to calculate the probabilities of formulas in ATF. For example, the formula $(\text{var } f_1 \rightarrow \text{var } f_2) \vee (\text{var } f_2 \rightarrow \text{var } f_1)$, considering only the two generators (f_1 and f_2), has denotational semantics $\{[f_1, f_2], [f_2, f_1]\}$ and the probability of the formula is the probability of $[f_1, f_2]$ or $[f_2, f_1]$ (but not both):

$$\begin{aligned}
&\text{FPr}\{(\text{var } f_1 \rightarrow \text{var } f_2) \vee (\text{var } f_2 \rightarrow \text{var } f_1)\} \\
&= \text{Pr}_{\text{FS}}\{[f_1, f_2]\} + \text{Pr}_{\text{FS}}\{[f_2, f_1]\} && \text{by Eq. (4.37)} \\
&= \text{Pr}\{[f_1, f_2]\} + \text{Pr}\{[f_2, f_1]\} && \text{by Eq. (4.36)} \\
&= \int_0^t P'_2(x)P_1(x)dx + \int_0^t P'_1(x)P_2(x)dx && \text{by Eq. (4.34)} \\
&= \int_0^t (P'_2(x)P_1(x) + P'_1(x)P_2(x)) dx && \text{by sum of } \int \\
&= \int_0^t (P_1(x)P_2(x))' dx && \text{by inv. deriv. product} \\
&= P_1(t) \times P_2(t)
\end{aligned} \tag{4.40}$$

In Eq. (4.40) we demonstrated that the probability of a formula $(\text{var } f_1 \rightarrow \text{var } f_2) \vee (\text{var } f_2 \rightarrow \text{var } f_1)$ is equal to the probability of the traditional AND probability $(\text{var } f_1 \wedge \text{var } f_2)$. This is expected as these two formulas are equivalent, as shown in Eq. (4.25b).

Another example including complement is the formula $\text{var } f_1 \wedge \text{var } f_2 \wedge \neg \text{var } f_3$:

$$\begin{aligned}
S &= \text{var } f_1 \wedge \text{var } f_2 \wedge \neg \text{var } f_3 \\
\text{Pr}\{S\} &= \text{Pr}_{\text{FS}}\{[f_1, f_2]\} + \text{Pr}_{\text{FS}}\{[f_2, f_1]\} && \text{by Eq. (4.37)} \\
&= \text{Pr}\{[f_1, f_2]\} \times (1 - P_3(t)) + \text{Pr}\{[f_2, f_1]\} \times (1 - P_3(t)) && \text{by Eq. (4.36)} \\
&= P_1(t) \times P_2(t) \times (1 - P_3(t)) && \text{by Eq. (4.40)}
\end{aligned} \tag{4.41}$$

Using Eq. (4.37), and for generators f_1 and f_2 , we demonstrate the equivalence to

the probability of a traditional **OR** operator, calculated using the denotational semantics:

$$\begin{aligned}
 S &= \mathbf{var} f_1 \vee \mathbf{var} f_2 \\
 \text{FPr}\{S\} &= \text{Pr}_{\text{FS}}\{[f_1]\} + \text{Pr}_{\text{FS}}\{[f_2]\} + \\
 &\quad \text{Pr}_{\text{FS}}\{[f_1, f_2]\} + \text{Pr}_{\text{FS}}\{[f_2, f_1]\} && \text{by Eq. (4.37)} \\
 &= \text{Pr}\{[f_1]\} \times (1 - P_2(t)) + \text{Pr}\{[f_2]\} \times (1 - P_1(t)) + \\
 &\quad P_1(t) \times P_2(t) && \text{by Eqs. (4.36) and (4.40)} \\
 &= P_1(t) \times (1 - P_2(t)) + P_2(t) \times (1 - P_1(t)) + \\
 &\quad P_1(t) \times P_2(t) \\
 &= P_1(t) + P_2(t) - P_1(t) \times P_2(t)
 \end{aligned} \tag{4.42}$$

We show an equivalence using the formula probability FPr for generators f_1 and f_2 :

$$\begin{aligned}
 \text{FPr}\{\mathbf{var} f_1 \wedge \mathbf{var} f_2\} &= \text{FPr}\{\mathbf{var} f_1\} \times \text{FPr}\{\mathbf{var} f_2\} \\
 \text{Pr}_{\text{FS}}\{[f_1, f_2]\} + \text{Pr}_{\text{FS}}\{[f_2, f_1]\} &= (\text{Pr}_{\text{FS}}\{[f_1]\} + \text{Pr}_{\text{FS}}\{f_1, f_2\} + \text{Pr}_{\text{FS}}\{f_2, f_1\}) \times \\
 &\quad (\text{Pr}_{\text{FS}}\{[f_2]\} + \text{Pr}_{\text{FS}}\{f_1, f_2\} + \text{Pr}_{\text{FS}}\{f_2, f_1\}) \\
 P_1(t) \times P_2(t) &= (P_1(t) \times (1 - P_2(t)) + P_1(t) \times P_2(t)) \times \\
 &\quad (P_2(t) \times (1 - P_1(t)) + P_1(t) \times P_2(t)) \\
 &= (P_1(t) - P_1(t) \times P_2(t) + P_1(t) \times P_2(t)) \times \\
 &\quad (P_2(t) - P_2(t) \times P_1(t) + P_1(t) \times P_2(t)) \\
 &= P_1(t) \times P_2(t)
 \end{aligned} \tag{4.43}$$

Finally, we propose that the formula probability calculation of a greater set of generators is the same of a smaller one. For example, for $\mathbf{var} f_1 \wedge \mathbf{var} f_2$ and generators f_1, f_2 , and f_3 :

$$\begin{aligned}
 \text{FPr}\{\mathbf{var} f_1 \wedge \mathbf{var} f_2\} &= \text{Pr}_{\text{FS}}\{[f_1, f_2]\} + \text{Pr}_{\text{FS}}\{[f_2, f_1]\} + \\
 &\quad \text{Pr}_{\text{FS}}\{[f_1, f_2, f_3]\} + \dots + \text{Pr}_{\text{FS}}\{[f_3, f_2, f_1]\} \\
 &= P_1(t) \times P_2(t) \times (1 - P_3(t)) + P_1(t) \times P_2(t) \times P_3(t) \\
 &= P_1(t) \times P_2(t) - P_1(t) \times P_2(t) \times P_3(t) + \\
 &\quad P_1(t) \times P_2(t) \times P_3(t) \\
 &= P_1(t) \times P_2(t)
 \end{aligned} \tag{4.44}$$

which is the same calculation as shown in Eq. (4.43). Thus, the probability calculation is not sensitive to a particular set of generators.

4.4.3 Formal acceptance criteria

To enable the formal verification of structure expressions we use the concept of *acceptance criteria*. Safety requirements are written in terms of the properties of an FT , for example: (i) no single failure should cause a critical failure (the length the $MCSeqs$ should be greater than 1), or (ii) the probability of all critical failure should be less than P_x . To check these requirements we translate these requirements into a value and verify in the theorem prover.

For the two analysis shown in this section, we define the two acceptance criteria:

$$|F|^{>n} = \text{Min}(\{|xs| \mid xs \in [F]\}) > n \quad \text{length of } MCSeqs \quad (4.45a)$$

$$\Pr\{F\}^{<P_x} = FPr\{F\} < P_x \quad \text{root-event probability} \quad (4.45b)$$

Both equations have Boolean return value, which can be verified by a theorem prover.

Using the formal acceptance criteria, safety requirements as stated in the beginning of this section are:

$|F|^{>1}$: the minimum length of the $MCSeqs$ of F are higher than 1;

$\Pr\{F\}^{<10^{-9}}$: the probability of the top event of F shall be less than 10^{-9} .

The verification of the acceptance criteria is illustrated with the probability calculation of a formula in Section 6.5.

4.5 Mapping CSP_M traces to ATF

In our previous work [28, 27] we reported a strategy to inject faults in a CSP_M model generated from an architectural model of a system in Simulink. Using a model-checker we were able to obtain failure traces with the injected faults, which we produced failure expressions in Boolean algebra. Thus, the order-related information was lost, as there are no means to represent them in Boolean algebra. For example, a trace that represents the occurrence of f_1 before f_2 was written as the expression $\text{var } f_1 \wedge \text{var } f_2$, which is the same as $\text{var } f_2 \wedge \text{var } f_1$.

Using the same strategy, but now mapping the traces to ATF we are able to analyse order-related failures. In this section we show how to map the same failure traces obtained by the strategy reported in the work [28] to ATF .

The mapping function takes the set of traces as input and produces a structure expression in ATF . Each event in the traces becomes a variable, and each list becomes an $XBefore$ with the conjunction ($ANDs$) of the variables of the remaining generators. The

following recursive definitions describe the mapping function.

$$\langle [] \rangle_{XB} = \top \quad (4.46a)$$

$$\langle [f] \rangle_{XB} = \mathbf{var} f \quad (4.46b)$$

$$\langle [f_1] @ tr \rangle_{XB} = \mathbf{var} f_1 \rightarrow \langle tr \rangle_{XB} \quad (4.46c)$$

$$\langle \{tr_1, tr_2, \dots, tr_n\} \rangle_{XB} = \bigvee_{i \in \{1, \dots, n\}} \left(\langle tr_i \rangle_{XB} \wedge \neg \bigvee_{j \in \text{Gen-set } tr_i} \mathbf{var} f_j \right) \quad (4.46d)$$

where @ concatenates two traces. The following examples show how it works for generators f_1, f_2, f_3 :

$$\langle [f_1] \rangle_{XB} = \mathbf{var} f_1 \wedge \neg (\mathbf{var} f_2 \vee \mathbf{var} f_3) \quad (4.47a)$$

$$\langle [f_1, f_2] \rangle_{XB} = \mathbf{var} f_1 \rightarrow \mathbf{var} f_2 \wedge \neg \mathbf{var} f_3 \quad (4.47b)$$

$$\langle [f_3, f_2, f_1] \rangle_{XB} = \mathbf{var} f_3 \rightarrow (\mathbf{var} f_2 \rightarrow \mathbf{var} f_1) \quad (4.47c)$$

$$\begin{aligned} \langle \{[f_1], [f_1, f_2]\} \rangle_{XB} = & (\mathbf{var} f_1 \wedge \neg \mathbf{var} f_2 \wedge \neg \mathbf{var} f_3) \vee \\ & ((\mathbf{var} f_1 \rightarrow \mathbf{var} f_2) \wedge \neg \mathbf{var} f_3) \end{aligned} \quad (4.47d)$$

5 Reasoning about fault activation



The Activation Logic proposed in this work emerges from the need to analyse the behaviour of a system when a subset of the faults have been triggered in some order, and to provide completeness analysis of system behaviour. There are at least two strategies to use **AL** to obtain structure expressions of **SFT**, **TFT**, or **DFT**: (i) model systems directly in **AL**, and (ii) obtaining operational mode expressions extracted from failure traces, as shown in the work reported in [52]. In approaches as those reported in [20, 3], behavioural completeness is left for the analyst. Using tautology and the indication of undefined nominal values, we ensure that no situation is left forgotten. That is, modelling is behaviourally complete.

The Activation Logic associates: (i) an operational mode, and (ii) the expression of fault events that *activates* the operational mode or error event. The expressions of fault events can be written in any algebra that provides tautology and contradiction properties. Boolean algebra and the **ATF** provide both. Thus, **AL** is parametrized by: (i) an algebra that provides at least tautology and contradiction, and (ii) operational modes. Figure 29 depicts an overview of **AL**.

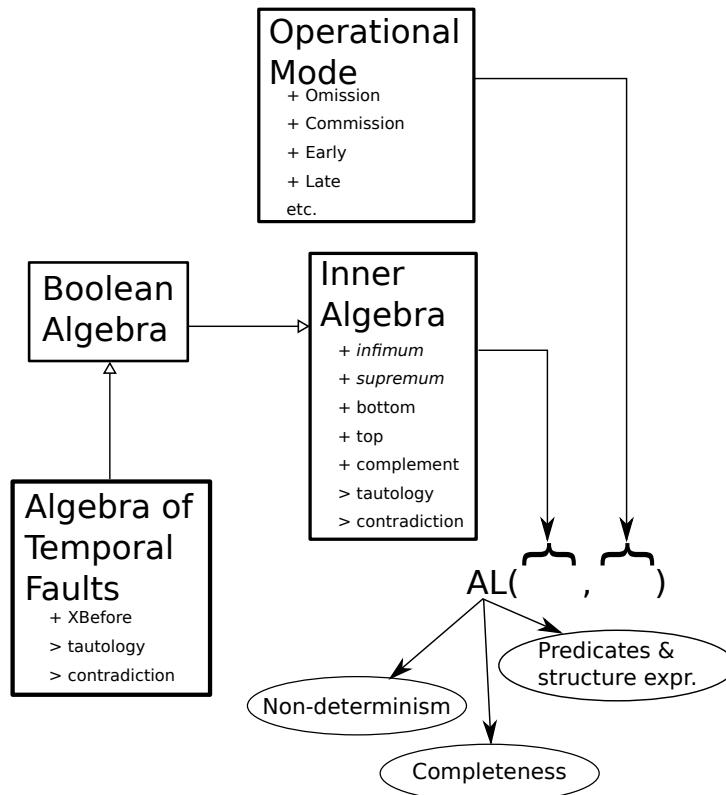


Figure 29 – **AL** overview

We summarise the properties of the **AL** as follows:

1. No expression predicate is a contradiction: there are no *false* predicates in activation expressions;
2. The predicates in the terms of an expression consider all possible situations: expression tautology;
3. There are no two terms with exactly the same operational mode: all expression terms are related to a unique operational mode.

These properties form the *healthiness conditions* [89] of an expression in the **AL**.

We show the general form of the **AL** to model faults in Section 5.1, the healthiness conditions to normalize expressions in Section 5.2, how to identify non-determinism in an expression in Section 5.3, and the predicate notation to analyse systems and model fault propagation in Section 5.4.

5.1 The Activation Logic Grammar

Each term in **AL** is a pair of a predicate and an operational mode. The predicate is written in either Boolean algebra, **ATF**, or any algebra that provides these properties: tautology and contradiction. We assume that the set of possible faults on a system is finite and that each variable declared in a predicate represents a fault event.

The operational mode has two generic values: (i) Nominal, and (ii) Failure. Nominal values either determine a value, or an undefined value (in this case, the constant value “*undefined*” is assumed). Failure values denote an erroneous behaviour, which can be a total failure (for example, signal omission) or a failure that causes degradation (for example, a signal below or above its nominal range). The choice of the operational modes depends on the system being analysed and its definition is generic and is left for the analyst. For the **AL**, it is sufficient to specify that it is an erroneous behaviour.

The grammar is parametrized by the syntax of an algebra (**Algebra**) and a set of operational modes (**OperModes**). The initial rules of the grammar are defined as follows:

AL(Algebra, OperModes)	= TERM(Algebra, OperModes)
	TERM(Algebra, OperModes)
	‘ ’ AL(Algebra, OperModes)
TERM(Algebra, OperModes)	= ‘(’ Algebra ‘,’ OM(OperModes) ‘)’
OM(OperModes)	= ‘Nominal’ NominalValue
	‘Failure’ OperModes
NominalValue	= ‘undefined’ Number
Number	= Integer Bool Decimal

The denotational semantics of the expressions in [AL](#) is a set of pairs. The predicate in each term of an expression depends on the semantics of the inner algebra. Thus the predicate evaluates to either *true* (\top) or *false* (\perp) depending on the valuation in the algebra. In what follows we show a sketch of the denotational semantics of [AL](#).

$$\begin{aligned} (P_1, O_1) &\mapsto \{(P_1, O_1)\} \\ (P_1, O_1) | (P_2, O_2) &\mapsto \{(P_1, O_1), (P_2, O_2)\} \\ \text{Nominal 100} &\mapsto \text{Nominal 100} \\ \text{Nominal undefined} &\mapsto \text{Nominal } \textit{undefined} \\ \text{Failure Omission} &\mapsto \text{Failure } \textit{Omission} \end{aligned}$$

In an expression, if the i^{th} predicate evaluates to *true* (\top), we say that the i^{th} operational mode is *activated*. To simplify the presentation of the expressions and to ease the understanding, we use the denotational semantics in the remainder of this [article](#) (the right-hand side of the sketch above). Thus, instead of using $\text{Exp} = (P_1, O_1) | (P_2, O_2)$ we will use $\text{Exp} = \{(P_1, O_1), (P_2, O_2)\}$

In this section, to illustrate the properties and possible analyses, we use an example of a system with faults A and B and the following outputs:

- O_1 : when A is active;
- O_2 : when B is active;
- O_3 : when A is active, but B is not;
- O_4 : when A or B are active.

The expression for this example in [AL](#) is:

$$S = \{(A, O_1), (B, O_2), (A \wedge \neg B, O_3), (A \vee B, O_4)\} \quad (5.1)$$

We use Eq. (5.1) on the following sections in this chapter to illustrate [AL](#).

In this example we see that one of the healthiness conditions is not satisfied: when for instance, A and B are both inactive ($\neg(A \wedge B)$), there is no explicit output defined. In [Section 6.4](#) we show a more detailed case study to illustrate the reasoning about temporal faults. In the next section, we show how to normalise the expression, so that the three healthiness conditions are satisfied.

5.2 Healthiness Conditions

The healthiness conditions are fix points of a language. The property is defined as a function of an expression and returns another expression. For example, if a healthiness condition H is satisfied for an expression Exp , we have $H(\text{Exp}) = \text{Exp}$.

In what follows we show the three healthiness conditions for the **AL**. All definitions in this section requires an algebra that satisfies the following properties:

contradiction: the expression always evaluates to *false*;

tautology: the expression always evaluates to *true*.

5.2.1 H₁: No predicate is a contradiction

This property is very simple and it is used to eliminate any term that has a predicate that always evaluates to false.

Definition 5.1. Let exp be an expression in the **AL**, then:

$$\text{H}_1(\text{exp}) = \{ (P, O) \mid (P, O) \in \text{exp} \bullet \neg\text{contradiction}(P) \} \quad (5.2)$$

where the operator \in indicates that a term is present in the expression.

Applying the first healthiness condition to our example results in:

$$\text{H}_1(S) = S$$

Thus, we conclude that S is H_1 -healthy.

5.2.2 H₂: All possibilities are covered

This property is used to make explicit that there are uncovered operational modes. In this case, there is a combination of variables in the algebra that was not declared in the expression. Very often the focus when modelling faults is on erroneous behaviour. So we assume that such an uncovered operational mode is nominal, but has an undefined value.

Definition 5.2. Let exp be an expression in the **AL**, and τ is:

$$\tau = \neg \left(\bigvee_{(P,O) \in \text{exp}} P \right)$$

then:

$$\text{H}_2(\text{exp}) = \begin{cases} \text{exp}, & \text{if } \text{contradiction}(\tau) \\ \text{exp} \cup \{(\tau, \text{Nominal } \textit{undefined})\}, & \text{otherwise} \end{cases} \quad (5.3)$$

This property checks erroneous behaviour completeness. If the expression is already complete, all possibilities are already covered, and the expression is healthy. Otherwise, a term containing the missing terms is introduced using the Nominal *undefined*.

Applying the second healthiness condition to our example results in the following expression after simplification:

$$H_2(S) = S \cup \{(\neg A \wedge \neg B, \text{Nominal } \textit{undefined})\}$$

Thus, we conclude that S is not H_2 -healthy.

5.2.3 H_3 : There are no two terms with exactly the same operational mode

This property merges terms that contain the same operational mode. It avoids unnecessary formulas and may reduce the expression.

Definition 5.3. Let exp be an expression in the [AL](#). Then:

$$\begin{aligned} H_3(\text{exp}) = \{ & (P_1, O_1) \mid (P_1, O_1) \in \text{exp} \wedge \\ & \forall (P_2, O_2) \in \text{exp} \bullet (P_1, O_1) = (P_2, O_2) \vee O_1 \neq O_2 \} \cup \\ & \{(P_1 \vee P_2, O_1) \mid (P_1, O_1), (P_2, O_2) \in \text{exp} \wedge O_1 = O_2\} \end{aligned} \quad (5.4)$$

Applying H_3 in the example in the beginning of the chapter, we conclude that S is H_3 -healthy. On the other hand, if we consider an S' system being a copy of S , but making $O_1 = O_2$, then:

$$H_3(S') = \{(A \vee B, O_1), (A \wedge \neg B, O_3), (A \vee B, O_4)\}$$

Thus, we conclude that S' is not H_3 -healthy.

5.2.4 Healthy expression

To obtain a healthy expression, we apply all three healthiness conditions. The order of application of each healthiness condition does not change the resulting expression. The healthiness function is written as composition of functions as follows:

$$H = H_1 \circ H_2 \circ H_3 \quad (5.5)$$

After applying the three healthiness conditions to S , the resulting expression is:

$$\begin{aligned} H(S) = \{ & (A, O_1), (B, O_2), \\ & (A \wedge \neg B, O_3), (A \vee B, O_4), \\ & (\neg A \wedge \neg B, \text{Nominal } \textit{undefined}) \} \end{aligned}$$

The healthiness conditions are useful to faults modelling, aiding the faults analyst to check contradictions and completeness. Also, obtaining safe predicates is only possible in healthy expressions. In the next section, we show how to verify non-determinism in [AL](#) expressions.

5.3 Non-determinism

Non-determinism is usually an undesirable property. Thus, the analysis shall consider the activation of faults even if the fault might or not be active.

To identify non-determinism, we can check for the negation of a contradiction in a pair of predicates in the algebra.

Definition 5.4 (Non-determinism). *Let \exp be an expression in AL .*

$$\begin{aligned} \text{nondeterministic}(\exp) = & \exists (P_1, O_1), (P_2, O_2) \in \exp \bullet \\ & \neg\text{contradiction}(P_1 \wedge P_2) \end{aligned} \quad (5.6)$$

If there is at least one combination that evaluates $P_1 \wedge P_2$ to true (it is not a contradiction), then \exp is non-deterministic. Our example is clearly non-deterministic as at least $A \wedge (A \vee B)$ is not a contradiction.

To analyse components and systems, and to model faults propagation, a predicate notation is shown in the next section. The predicate notation offers two additional ways to check non-determinism.

5.4 Predicate Notation

The Activation Logic needs a special notation to enable the analysis of: (i) a particular faults expression, or (ii) a propagation in components. Such a special notation extracts predicates in the algebra given an observable failure of the system (an undesired operational mode).

Definition 5.5 (Predicate). *Let \exp be an expression in AL , and O_x an operational mode. A predicate over \exp that matches O_x is described as:*

$$\langle |\text{out}(\exp) = O_x| \rangle \iff \exists (P, O) \in \text{H}(\exp) \mid O = O_x \bullet P \quad (5.7)$$

The predicate notation function returns a predicate in the algebra. For the example in the beginning of this section, the predicate for O_2 is obtained as follows:

$$\langle |\text{out}(S) = O_2| \rangle = B$$

To allow fault propagation of components we need another special notation. It expands the modes of an expression with a predicate in the inner algebra.

Definition 5.6 (Modes). *Let \exp be an expression in AL , and P a predicate in the inner algebra, then:*

$$\text{modes}(\exp, P) = \{(P_i \wedge P, O_i) \mid (P_i, O_i) \in \text{H}(\exp)\} \quad (5.8)$$

Finally, to check the possible outputs, we need a function to obtain a set of outputs given an expression.

Definition 5.7 (Activation). *Let exp be an expression in AL , and P_x a predicate in the inner algebra, then:*

$$\text{activation}(exp, P_x) = \{O | (P, O) \in H(exp) \wedge \text{tautology}(P_x \implies P)\} \quad (5.9)$$

Non-determinism can also be checked using the predicate notation and the activation property:

$$\text{activation}(S, A \wedge \neg B) = \{O_1, O_3\} \quad (5.10a)$$

$$\langle |\text{out}(S) = O_1| \rangle \wedge \langle |\text{out}(S) = O_3| \rangle = A \wedge \neg B \quad (5.10b)$$

Equation (5.10a) shows that both O_1 and O_3 can be observed if $A \wedge \neg B$ is *true*. Equation (5.10b) states that if the possible operational modes of healthy S are O_1 and O_3 , then the predicate is $A \wedge \neg B$. Non-determinism is the possibility of observing two different failures (O_1 and O_3) for the same failure expression ($A \wedge \neg B$) in the algebra. In the next chapter, we show a practical case study using these properties and notations.



6 Case study

Our industrial partner provided us with the Simulink model of an Actuator Control System (depicted in Figure 26). The failure expression of this system (that is, for each of its constituent components) was also provided by our industrial partner (we show some of them in Table 7). In what follows we illustrate our strategy using the Monitor component.

A monitor component is a system commonly used for fault tolerance [90, 91]. Initially, the monitor connects the main input (power source on input port 1) with its output. It observes the value of this input port and compares it to a threshold. If the value is below the threshold, the monitor disconnects the output from the main input and connects to the secondary input. We present the Simulink model for this monitor in Figure 27.



Sensors and actuators are used to improve safety by taking measures to decrease potential failures, as the leak protection system reported in [9], and shown in Subsection 3.4.3. A sensor is installed in a room that may have gas leakage. If the sensor detects a gas leak, then an actuator—a controlled valve—closes the gas flow. A second valve diverts the gas flow if a high pressure is detected due the first valve closing.

Now we show five contributions: (i) using ATF, but only with Boolean operators, thus ignoring ordering, we can obtain the same results obtained in [28], (ii) representing each of the fault traces reported in [28] as a term in our proposed ATF, using the mapping function shown in Section 4.5, (iii) modelling faults of the monitor using AL, using expressions in Boolean Algebra, (iv) modelling faults of the monitor with AL, but using ATF as the inner algebra, and (v) obtaining failure probability from a formula with explicit NOT operators without considering the consensus law nor the theory shown in [9]. Similarly to the association of fault events of Table 7 in Section 3.5, we associate the fault events as:

$$b_1 = \text{LowPower-In1}$$

$$B_1 = \mathbf{var} b_1$$

$$b_2 = \text{LowPower-In2}$$

$$B_2 = \mathbf{var} b_2$$

$$f = \text{SwitchFailure}$$

$$F = \mathbf{var} f$$

and for the leak detection system, we associate fault events as:

$$prv = \text{the pressure relief valve fails}$$

$$PRV = \mathbf{var} prv$$

$$i_1 = \text{there is an ignition source in room 1}$$

$$I_1 = \mathbf{var} i_1$$

$$l = \text{there is a gas leak in room 1}$$

$$L = \mathbf{var} l$$

$$val = \text{the isolation valve fails}$$

$$VAL = \mathbf{var} val$$

6.1 From traces to structure expressions with Boolean operators

In this section we show that the same result reported in [28] in terms of static failure expression (or Boolean propositions) can be obtained with our Boolean operator without using **XBefore**. Similarly to the mapping function shown in Section 4.5, we define a mapping function from traces to **ATF** with Boolean operators only as:

$$\langle [] \rangle_{bool} = \top \quad (6.1a)$$

$$\langle [f] \rangle_{bool} = \text{var } f \quad (6.1b)$$

$$\langle [f_1] @ tr \rangle_{bool} = \text{var } f_1 \wedge \langle tr \rangle_{bool} \quad (6.1c)$$

$$\langle \{tr_1, tr_2, \dots, tr_n\} \rangle_{bool} = \bigvee_{i \in \{1, \dots, n\}} \left(\langle tr_i \rangle_{bool} \wedge \neg \bigvee_{j \in \text{Gen}_{tr_i}} \text{var } f_j \right) \quad (6.1d)$$

The only difference of the mapping function, when considering Boolean operators only, is Eq. (6.1c). Equations (6.1a), (6.1b) and (6.1d) are similar to Eqs. (4.46a), (4.46b) and (4.46d)

For each trace shown in Section 3.5, the mapping function generates the following expressions

- TRACE 1: $\langle [f, b_2] \rangle_{bool} = F \wedge B_2$
- TRACE 2: $\langle [b_2, f] \rangle_{bool} = B_2 \wedge F$
- TRACE 3: $\langle [b_1, b_2] \rangle_{bool} = B_1 \wedge B_2$
- TRACE 4: $\langle [b_2, b_1] \rangle_{bool} = B_2 \wedge B_1$
- TRACE 5: $\langle [b_1, f] \rangle_{bool} = B_1 \wedge F$
- TRACE 6: $\langle [b_1, f, b_2] \rangle_{bool} = B_1 \wedge F \wedge B_2$
- TRACE 7: $\langle [b_1, b_2, f] \rangle_{bool} = B_1 \wedge B_2 \wedge F$
- TRACE 8: $\langle [b_2, b_1, f] \rangle_{bool} = B_2 \wedge B_1 \wedge F$
- TRACE 9: $\langle [f, b_1, b_2] \rangle_{bool} = F \wedge B_1 \wedge B_2$
- TRACE 10: $\langle [f, b_2, b_1] \rangle_{bool} = F \wedge B_2 \wedge B_1$
- TRACE 11: $\langle [b_2, f, b_1] \rangle_{bool} = B_2 \wedge F \wedge B_1$

They represent the same faults shown in Section 3.5. Applying the mapping function, Eq. (6.1d), for the previously shown set of traces, we obtain the following expression in **ATF** (and in **FBA**):

$$M_{bool} = (B_1 \wedge B_2) \vee (F \wedge (B_1 \vee B_2)) \quad (6.2)$$

which is equivalent to our industrial partner's failure expression shown in Table 7. This shows that **ATF** can represent (static) failure expression as in our previous work [28].

6.2 From traces to structure expressions with XBefore

Now, by using ATF with the XBefore operator and the mapping function shown in Eqs. (4.46a) to (4.46d), we can capture each possible individual sequences as generated by the work [28]:

```

TRACE 1:  $\langle [ f, b_2 ] \rangle_{XB} = (F \rightarrow B_2)$ 
TRACE 2:  $\langle [ b_2, f ] \rangle_{XB} = (B_2 \rightarrow F)$ 
TRACE 3:  $\langle [ b_1, b_2 ] \rangle_{XB} = (B_1 \rightarrow B_2)$ 
TRACE 4:  $\langle [ b_2, b_1 ] \rangle_{XB} = (B_2 \rightarrow B_1)$ 
TRACE 5:  $\langle [ b_1, f ] \rangle_{XB} = (B_1 \rightarrow F)$ 
TRACE 6:  $\langle [ b_1, f, b_2 ] \rangle_{XB} = B_1 \rightarrow (F \rightarrow B_2)$ 
TRACE 7:  $\langle [ b_1, b_2, f ] \rangle_{XB} = B_1 \rightarrow (B_2 \rightarrow F)$ 
TRACE 8:  $\langle [ b_2, b_1, f ] \rangle_{XB} = B_2 \rightarrow (B_1 \rightarrow F)$ 
TRACE 9:  $\langle [ f, b_1, b_2 ] \rangle_{XB} = F \rightarrow (B_1 \rightarrow B_2)$ 
TRACE 10:  $\langle [ f, b_2, b_1 ] \rangle_{XB} = F \rightarrow (B_2 \rightarrow B_1)$ 
TRACE 11:  $\langle [ b_2, f, b_1 ] \rangle_{XB} = B_2 \rightarrow (F \rightarrow B_1)$ 

```

Using the mapping function, Eq. (4.46d), for the previously shown set of traces, we obtain:

$$\begin{aligned}
M_A &= (F \rightarrow B_2 \wedge \neg B_1) \vee (B_2 \rightarrow F \wedge \neg B_1) \vee (B_1 \rightarrow B_2 \wedge \neg F) \vee \\
&\quad (B_2 \rightarrow B_1 \wedge \neg F) \vee (B_1 \rightarrow F \wedge \neg B_2) \vee (B_1 \rightarrow (F \rightarrow B_2)) \vee \\
&\quad (B_1 \rightarrow (B_2 \rightarrow F)) \vee (B_2 \rightarrow (B_1 \rightarrow F)) \vee (F \rightarrow (B_1 \rightarrow B_2)) \vee \\
&\quad (F \rightarrow (B_2 \rightarrow B_1)) \vee (B_2 \rightarrow (F \rightarrow B_1)) \\
&= (F \wedge B_2 \wedge \neg B_1) \vee (B_1 \wedge B_2 \wedge \neg F) \vee (B_1 \rightarrow F \wedge \neg B_2) \vee \\
&\quad (B_1 \rightarrow (F \rightarrow B_2)) \vee (B_1 \rightarrow (B_2 \rightarrow F)) \vee (B_2 \rightarrow (B_1 \rightarrow F)) \vee \\
&\quad (F \rightarrow (B_1 \rightarrow B_2)) \vee (F \rightarrow (B_2 \rightarrow B_1)) \vee (B_2 \rightarrow (F \rightarrow B_1)) \quad \text{by Eq. (4.27c)} \\
&= (F \wedge B_2 \wedge \neg B_1) \vee (B_1 \wedge B_2 \wedge \neg F) \vee (B_1 \rightarrow F \wedge \neg B_2) \vee \\
&\quad (B_2 \wedge (B_1 \rightarrow F)) \vee (B_2 \wedge (F \rightarrow B_1)) \quad \text{by Eq. (4.28)} \\
&= (B_1 \wedge B_2) \vee (F \wedge B_2) \vee (B_1 \rightarrow F \wedge \neg B_2)
\end{aligned} \tag{6.3}$$

The semantics of the above expression is: (i) fault b_2 ($\text{var } b_2$) occurs and fault b_1 ($\text{var } b_1$) or fault f ($\text{var } f$) occurs, or (ii) fault b_1 occurs before fault f and fault b_2 does not occur, which is more precise than the expression found without considering order of events.

Expanding Eq. (6.2), we have:

$$(B_1 \wedge B_2) \vee (F \wedge B_2) \vee (F \wedge B_1)$$

which differs from Eq. (6.3) only on terms: $F \wedge B_1$ (of M_{bool}) and $F \rightarrow B_1 \wedge \neg B_2$ (of M_A).

6.3 From AL to structure expressions with Boolean operators

The power source has only two possible operational modes: (i) the power source works as expected, providing a nominal value of $12V$, and (ii) it has an internal failure B_i , and its operational mode is “low power”. In AL it is modelled as:

$$PowerSource_i = \{(B_i, LP), (\neg B_i, \text{Nominal } 12V)\} \quad (6.4)$$

where LP is the LowPower failure. $PowerSource_i$ is healthy:

- H_1 -healthy: there is no contradiction in the expressions;
- H_2 -healthy: combining the expressions of the pairs in a disjunction, we obtain a tautology;
- H_3 -healthy: the operational modes of the pairs are distinct.

The monitor is a bit different because its behaviour depends not only on internal faults, but also on its inputs. We will now use the predicate notation defined in Section 5.4 to express fault propagation. As the monitor has two inputs and its behaviour is described in Figure 27, then it is a function of the expressions of both inputs:

$$\begin{aligned} Monitor_{bool}(in_1, in_2) = & \\ & \text{modes}(in_1, \langle |out(in_1) = \text{Nominal } X| \rangle \wedge \neg F) \cup \\ & \text{modes}(in_2, \neg \langle |out(in_1) = \text{Nominal } X| \rangle \wedge \neg F) \cup \\ & \text{modes}(in_2, \langle |out(in_1) = \text{Nominal } X| \rangle \wedge F) \cup \\ & \text{modes}(in_1, \neg \langle |out(in_1) = \text{Nominal } X| \rangle \wedge F) \end{aligned} \quad (6.5)$$

where X is an unbound variable and assumes any value. The expression states the following:

- The monitor output is the same as in_1 if the output of in_1 is nominal and *there is no* internal failure in the monitor:

$$\text{modes}(in_1, \langle |out(in_1) = \text{Nominal } X| \rangle \wedge \neg F)$$

- The monitor output is the same as in_2 if the output of in_1 is not nominal and *there is no* internal failure in the monitor:

$$\text{modes}(in_2, \neg \langle |out(in_1) = \text{Nominal } X| \rangle \wedge \neg F)$$

- The monitor output is the converse of the previous two conditions if the internal failure F is active:

$$\begin{aligned} & \text{modes } (in_2, \langle | \text{out}(in_1) = \text{Nominal } X | \rangle \wedge F) \cup \\ & \text{modes } (in_1, \neg \langle | \text{out}(in_1) = \text{Nominal } X | \rangle \wedge F) \end{aligned}$$

The operational modes (observed behaviour) of the monitor depend on: (i) its internal fault, and (ii) propagated errors from its inputs. Composing the monitor with the two power sources, we obtain the AL expression of a power supply subsystem $System_{bool}$:

$$\begin{aligned} System_{bool} &= \\ & Monitor_{bool}(PowerSource_1, PowerSource_2) \\ &= \text{modes } (in_1, \neg B_1 \wedge \neg F) \cup \text{modes } (in_2, \neg \neg B_1 \wedge \neg F) \cup \\ & \quad \text{modes } (in_2, \neg B_1 \wedge F) \cup \text{modes } (in_1, \neg \neg B_1 \wedge F) \quad \text{by Eq. (5.7)} \\ &= \text{modes } (in_1, \neg B_1 \wedge \neg F) \cup \text{modes } (in_2, B_1 \wedge \neg F) \cup \\ & \quad \text{modes } (in_2, \neg B_1 \wedge F) \cup \text{modes } (in_1, B_1 \wedge F) \quad \text{by simplification} \\ &= \{(P_i \wedge \neg B_1 \wedge \neg F, O_i) \mid (P_i, O_i) \in in_1\} \cup \\ & \quad \{(P_i \wedge B_1 \wedge \neg F, O_i) \mid (P_i, O_i) \in in_2\} \cup \\ & \quad \{(P_i \wedge \neg B_1 \wedge F, O_i) \mid (P_i, O_i) \in in_2\} \cup \\ & \quad \{(P_i \wedge B_1 \wedge F, O_i) \mid (P_i, O_i) \in in_1\} \quad \text{by Eq. (5.8)} \\ &= \{(B_1 \wedge \neg B_1 \wedge \neg F, LP), \\ & \quad (\neg B_1 \wedge \neg B_1 \wedge \neg F, \text{Nominal } 12V), \\ & \quad (B_2 \wedge B_1 \wedge \neg F, LP), \\ & \quad (\neg B_2 \wedge B_1 \wedge \neg F, \text{Nominal } 12V), \\ & \quad (B_2 \wedge \neg B_1 \wedge F, LP), \\ & \quad (\neg B_2 \wedge \neg B_1 \wedge F, \text{Nominal } 12V), \\ & \quad (B_1 \wedge B_1 \wedge F, LP), \\ & \quad (\neg B_1 \wedge B_1 \wedge F, \text{Nominal } 12V)\} \quad \text{replacing vars} \end{aligned}$$

Simplifying and applying H₁, we obtain:

$$\begin{aligned} H_1(System_{bool}) &= \\ & \{(\neg B_1 \wedge \neg F, \text{Nominal } 12V), (B_2 \wedge B_1 \wedge \neg F, LP), \\ & \quad (\neg B_2 \wedge B_1 \wedge \neg F, \text{Nominal } 12V), (B_2 \wedge \neg B_1 \wedge F, LP), \\ & \quad (\neg B_2 \wedge \neg B_1 \wedge F, \text{Nominal } 12V), (B_1 \wedge F, LP)\} \end{aligned}$$

Applying, H_3 , we simplify to:

$$\begin{aligned}
 & H_3 \circ H_1 (System_{\text{bool}}) \\
 &= \left\{ \begin{array}{l} (\neg B_1 \wedge \neg F) \vee \\ (B_1 \wedge \neg B_2 \wedge \neg F) \vee, \text{Nominal } 12V \\ (\neg B_1 \wedge \neg B_2 \wedge F) \end{array} \right\}, \\
 & \quad \left\{ \begin{array}{l} (B_1 \wedge B_2 \wedge \neg F) \vee \\ (\neg B_1 \wedge B_2 \wedge F) \vee, LP \\ (B_1 \wedge F) \end{array} \right\} \\
 &= \{ ((\neg B_1 \wedge \neg B_2) \vee \neg F \wedge (\neg B_1 \vee \neg B_2), \text{Nominal } 12V), \\
 & \quad (F \wedge (B_1 \vee B_2) \vee (B_1 \wedge B_2), LP) \}
 \end{aligned}$$

The monitor expression is H_2 -healthy (the predicates are complete), thus:

$$H_2 \circ H_3 \circ H_1 (System_{\text{bool}}) = H_3 \circ H_1 (System_{\text{bool}})$$

The resulting expression for the monitor after applying all healthiness conditions is:

$$\begin{aligned}
 H (System_{\text{bool}}) &= \{ ((\neg B_1 \wedge \neg B_2) \vee \neg F \wedge (\neg B_1 \vee \neg B_2), \text{Nominal } 12V), \\
 & \quad (F \wedge (B_1 \vee B_2) \vee (B_1 \wedge B_2), LP) \}
 \end{aligned} \tag{6.6}$$

The operational modes of $System_{\text{bool}}$ is either Nominal 12V or LP (low power).

Finally, we obtain the *low power* structure expression (see Table 7) using the predicate notation:

$$\langle |out (System_{\text{bool}}) = LP | \rangle \iff F \wedge (B_1 \vee B_2) \vee (B_1 \wedge B_2)$$

The monitor expression also indicates that if the switch is operational ($\neg F$) and at least one PowerSource is operational ($\neg B_1 \vee \neg B_2$), the monitor output is nominal. But if at least one PowerSource is faulty ($B_1 \vee B_2$) and the monitor has an internal failure (F) the system is not operational. These two sentences—written in AL using the predicate notation—are:

$$\begin{aligned}
 & \text{activation} (System_{\text{bool}}, \neg F \wedge (\neg B_1 \vee \neg B_2)) \\
 &= \{O | (P, O) \in H (System_{\text{bool}}) \wedge \\
 & \quad \text{tautology} (\neg F \wedge (\neg B_1 \vee \neg B_2) \implies P)\} \quad [\text{by Eq. (5.9)}] \\
 &= \{\text{Nominal } 12V\} \quad [\text{by simplification}] \tag{6.7a}
 \end{aligned}$$

$$\begin{aligned}
 & \text{activation} (System_{\text{bool}}, F \wedge (B_1 \vee B_2)) \\
 &= \{O | (P, O) \in H (System_{\text{bool}}) \wedge \\
 & \quad \text{tautology} (F \wedge (B_1 \vee B_2) \implies P)\} \quad [\text{by Eq. (5.9)}] \\
 &= \{LP\} \quad [\text{by simplification}] \tag{6.7b}
 \end{aligned}$$

6.4 From AL to structure expressions with XBefore

Now, let's consider the same system but with a subtle modification. As shown in [52], the order of the occurrence of faults may be relevant, and the qualitative and quantitative analyses results may be different than those results without considering the order of the occurrence of faults. Observing Figure 27, we see that if F activates before a failure in the first input of the monitor, then it would display a nominal behaviour. This is because the internal failure F anticipates switching to the second input. On the other hand, if the first input fails before F , then the monitor would switch to the second input, and then switch back due to the internal failure. We obtain the following expression for the monitor, now using the ATF:

$$\begin{aligned}
 Monitor_{XB}(in_1, in_2) = & \\
 & \text{modes}(in_1, \langle |out(in_1) = \text{Nominal } X | \rangle \wedge \neg F) \cup \\
 & \text{modes}(in_2, \neg \langle |out(in_1) = \text{Nominal } X | \rangle \wedge \neg F) \cup \\
 & \text{modes}(in_2, \langle |out(in_1) = \text{Nominal } X | \rangle \wedge F) \cup \\
 & \text{modes}(in_1, \neg \langle |out(in_1) = \text{Nominal } X | \rangle \rightarrow F) \cup \\
 & \text{modes}(in_2, F \rightarrow \neg \langle |out(in_1) = \text{Nominal } X | \rangle)
 \end{aligned} \tag{6.8}$$

where X is an unbound variable and assumes any value.

The difference to $System_{\text{bool}}$ (Eq. (6.5)) is only the finer analysis of the cases of erroneous behaviours of the first input and an internal failure. Note that the finer analysis splits the predicate

$$\neg \langle |out(in_1) = \text{Nominal } 12V | \rangle \wedge F \quad (\text{activates } in_1)$$

into:

$$\neg \langle |out(in_1) = \text{Nominal } 12V | \rangle \rightarrow F \quad (\text{activates } in_1)$$

and

$$F \rightarrow \neg \langle |out(in_1) = \text{Nominal } 12V | \rangle \quad (\text{activates } in_2)$$

We can assure that such a split is complete because the predicate notation evaluates to B_1 . As the operands satisfy all temporal properties (Eqs. (4.14) and (4.16) to (4.18)) and events independence (Eq. (4.23)), thus the law shown in Eq. (4.25b) is valid. For the first split item, the expected behaviour is the same as in_1 because the system switches to in_2 , but then an internal failure occurs, and it switches back to in_1 . For the second split item, it switches to in_2 due to an internal failure, then the first input fails, so the behaviour is similar to the nominal behaviour (see the second *modes* in Eq. (6.8)).

Following the similar expansions of Eq. (6.5), we obtain:

$$\begin{aligned}
 System_{XB} &= Monitor_{XB}(PowerSource_1, PowerSource_2) \\
 &= \{(B_1 \wedge \neg B_1 \wedge \neg F, LP), \\
 &\quad (\neg B_1 \wedge \neg B_1 \wedge \neg F, \text{Nominal } 12V), \\
 &\quad (B_2 \wedge B_1 \wedge \neg F, LP), \\
 &\quad (\neg B_2 \wedge B_1 \wedge \neg F, \text{Nominal } 12V), \\
 &\quad (B_2 \wedge \neg B_1 \wedge F, LP), \\
 &\quad (\neg B_2 \wedge \neg B_1 \wedge F, \text{Nominal } 12V), \\
 &\quad (B_1 \wedge B_1 \rightarrow F, LP), \\
 &\quad (\neg B_1 \wedge B_1 \rightarrow F, \text{Nominal } 12V)\}, \\
 &\quad (B_2 \wedge F \rightarrow B_1, LP), \\
 &\quad (\neg B_2 \wedge F \rightarrow B_1, \text{Nominal } 12V)\}
 \end{aligned}$$

Simplifying and applying H₁ to remove contradictions, we obtain:

$$\begin{aligned}
 H_1(System_{XB}) &= \\
 &\{(\neg B_1 \wedge \neg F, \text{Nominal } 12V), (B_2 \wedge B_1 \wedge \neg F, LP), \\
 &\quad (\neg B_2 \wedge B_1 \wedge \neg F, \text{Nominal } 12V), (B_2 \wedge \neg B_1 \wedge F, LP), \\
 &\quad (\neg B_2 \wedge \neg B_1 \wedge F, \text{Nominal } 12V), (B_1 \rightarrow F, LP), \\
 &\quad (B_2 \wedge F \rightarrow B_1, LP), (\neg B_2 \wedge F \rightarrow B_1, \text{Nominal } 12V)\}
 \end{aligned}$$

Applying H₃ to remove redundant terms with identical operational modes and

using the rules shown in Section 4.2, we simplify to:

$$\begin{aligned}
 & H_3 \circ H_1 (System_{XB}) \\
 &= \left\{ \begin{array}{l} (\neg B_1 \wedge \neg F) \vee \\ (B_1 \wedge \neg B_2 \wedge \neg F) \vee \\ (\neg B_1 \wedge \neg B_2 \wedge F) \vee \\ (\neg B_2 \wedge F \rightarrow B_1) \end{array}, \text{Nominal } 12V \right\}, \\
 & \quad \left\{ \begin{array}{l} (B_1 \wedge B_2 \wedge \neg F) \vee \\ (\neg B_1 \wedge B_2 \wedge F) \vee \\ (B_1 \rightarrow F) \vee \\ (B_2 \wedge F \rightarrow B_1) \end{array} \right\} \\
 &= \left\{ \begin{array}{l} (\neg B_1 \wedge \neg F) \vee \\ (B_1 \wedge \neg B_2 \wedge \neg F) \vee \\ (\neg B_1 \wedge \neg B_2 \wedge F) \vee \\ (\neg B_2 \wedge F \rightarrow B_1) \end{array}, \text{Nominal } 12V \right\}, \\
 & \quad \left\{ \begin{array}{l} (B_1 \wedge B_2 \wedge \neg F) \vee \\ (\neg B_1 \wedge B_2 \wedge F) \vee \\ (B_2 \wedge B_1 \rightarrow F) \vee, LP \\ (\neg B_2 \wedge B_1 \rightarrow F) \vee \\ (B_2 \wedge F \rightarrow B_1) \end{array} \right\} \\
 &= \{ ((\neg B_1 \wedge \neg B_2) \vee \neg F \wedge (\neg B_1 \vee \neg B_2) \vee \\
 & \quad \neg B_2 \wedge F \rightarrow B_1, \text{Nominal } 12V), \\
 & \quad ((B_1 \wedge B_2) \vee (B_2 \wedge F) \vee (\neg B_2 \wedge B_1 \rightarrow F), LP) \}
 \end{aligned}$$

The monitor expression is H_2 -healthy. Simplifying Boolean operators as usual, the XBefore expression is:

$$(\neg B_2 \wedge F \rightarrow B_1) \vee (\neg B_2 \wedge B_1 \rightarrow F)$$

which simplifies to

$$\neg B_2 \wedge F \wedge B_1 \quad \text{by Eq. (4.25b)}$$

Thus:

$$H_2 \circ H_3 \circ H_1 (System_{XB}) = H_3 \circ H_1 (System_{XB})$$

The resulting expression for the monitor after applying all healthiness conditions

is:

$$\begin{aligned} H(\text{System}_{XB}) = & \{ ((\neg B_1 \wedge \neg B_2) \vee \neg F \wedge (\neg B_1 \vee \neg B_2) \vee \\ & \neg B_2 \wedge F \rightarrow B_1, \text{Nominal } 12V), \\ & ((B_1 \wedge B_2) \vee (B_2 \wedge F) \vee \\ & (\neg B_2 \wedge B_1 \rightarrow F), LP) \} \end{aligned} \quad (6.9)$$

Finally, we obtain the *low power* structure expression of the monitor using the predicate notation:

$$\langle | \text{out}(\text{System}_{XB}) = LP | \rangle \iff (B_1 \wedge B_2) \vee (B_2 \wedge F) \vee (\neg B_2 \wedge B_1 \rightarrow F)$$

Thus, System_{XB} fails with LP if:

- Both power sources fail;
- The monitor fails to detect the nominal state of the first power source and the second power source is in a failure state;
- The monitor fails to detect the failure state of the first power source (the monitor fails after the failure of the first power source).

Note that if the monitor fails before the failure of the first power source, it fails to detect the operational mode of the first power source and switches to the second power source, which is in a nominal state (see expression $\neg B_2 \wedge F \rightarrow B_1$ in Eq. (6.9)).

6.5 Obtaining top-event probability with explicit NOT operators

In this section we show how to use **ATF** to obtain the same probability formula of Eq. (3.11).

We use Eq. (4.43) to split the calculations of the top-event structure expression shown in Eq. (3.9):

$$\begin{aligned} \text{FPr}\{L \wedge ((\neg VAL \wedge PRV) \vee (VAL \wedge I_1))\} = \\ \text{FPr}\{L\} \times \text{FPr}\{(\neg VAL \wedge PRV) \vee (VAL \wedge I_1)\} \end{aligned} \quad (6.10)$$

Then, we obtain the formula probability of the top-event probability of the structure

expression shown in Eq. (3.9) in ATF:

$$\begin{aligned} \text{FPr}\{L\} &= \text{Pr}_{\text{FS}}\{[l]\} && \text{by Eq. (4.44)} \\ &= P_l(t) && (6.11a) \end{aligned}$$

$$\begin{aligned} \text{FPr}\{(\neg VAL \wedge PRV) \vee \\ (VAL \wedge I_1)\} &= \text{Pr}_{\text{FS}}\{[prv]\} + \text{Pr}_{\text{FS}}\{[i_1, prv]\} + \\ &\quad \text{Pr}_{\text{FS}}\{[prv, i_1]\} + \text{Pr}_{\text{FS}}\{[val, i_1]\} + \\ &\quad \text{Pr}_{\text{FS}}\{[i_1, val]\} + \\ &\quad \text{Pr}_{\text{FS}}\{[val, i_1, prv]\} + \dots + \\ &\quad \text{Pr}_{\text{FS}}\{[prv, i_1, val]\} \end{aligned}$$

Note that we use the expression without the consensus law, but the “missing” term $PRV \wedge I_1$ appears naturally on the denotational semantics used in our proposed probability calculation.

$$\begin{aligned} \text{FPr}\{(\neg VAL \wedge PRV) \vee \\ (VAL \wedge I_1)\} &= P_{prv}(t) \times (1 - P_{i_1}(t)) \times (1 - P_{val}(t)) \\ &\quad P_{i_1}(t) \times P_{prv}(t) \times (1 - P_{val}(t)) \\ &\quad P_{val}(t) \times P_{i_1}(t) \times (1 - P_{prv}(t)) \\ &\quad P_{val}(t) \times P_{i_1}(t) \times P_{prv}(t) \\ &= P_{prv}(t) + P_{val}(t) \times P_{i_1}(t) - P_{prv}(t) \times P_{val}(t) && (6.11b) \end{aligned}$$

From Eqs. (6.10), (6.11a) and (6.11b), we obtain:

$$\text{FPr}\{TOP\} = P_l(t) \times (P_{prv}(t) + P_{val}(t) \times P_{i_1}(t) - P_{prv}(t) \times P_{val}(t)) \quad (6.12)$$

which is equivalent to Eq. (3.11).

7 Conclusion

In this work we presented a foundational theory to support a more precise representation of fault events as compared to our previous strategy for injecting faults [28]. The failure logic is essential for system safety assessment because it is used as basic input for building fault trees [25, 31, 92]. Furthermore, we still connect the strategy presented in [93] with the works reported in [31] (functional analysis) and in [92, 25] (safety assessment) because our new algebra is at least a Boolean algebra.

We also proposed a parametrized logic, the **AL**, that enables the analysis of systems depending on the expressiveness of a given algebra and a given set of operational modes. If **ATF** is used as a parameter, then the order of occurrence of faults can be considered. Other algebras, like ternary algebras [94] can be used, since they have tautology and contradiction properties. Although the **AL** is not as detailed as **AADL**, the predicate notation in conjunction with the **ATF** provides a richer assertion framework. Also, it is possible to verify non-determinism on the model, by: (i) verifying its existence with the nondeterministic function, (ii) providing an expression and obtaining the possible operational modes with the activation function, or (iii) using the predicate notation to obtain a predicate that enables two or more operational modes.

The work reported in [21, 20, 33] tackles simultaneity with “nearly simultaneous” events [95]. But we consider instantaneous events, like the work reported in [23], because we assume that simultaneity is probabilistically impossible.

The distinct lists representation in our algebra does not allow obtaining minimal cut sequences directly from the formula, similar to **FBA**s. The sets in an **FBA** formula are already the minimal cut sets. In our work, **ATF** allows us to find minimal cut sequences (with **XBefore**) from the formulas in **DNF** algebraically: each sub-expression is a minimal cut sequence.

Boolean formulas reduction can be achieved by: (i) application of Boolean laws, (ii) **BDDs**, or (iii) **FBA**s. We used Boolean and **XBefore** laws to reduce **ATF** formulas. The work reported in [42, 43] uses Sequential BDDs to reduce formulas with order-based operators. We plan to use similar concepts in a future work. A ternary tree with special nodes seems to be a solution, but we have not verified yet.

The works reported in [3, 66, 22, 21, 20] removed the **NOT** operator. Thus, the algebras defined there (to analyse **TFT** and **DFT**) resembles a Boolean algebra, but are not complete. The **ATF** allows such trees to have **NOT** operators and the analysis could be performed similarly to **SFT**. Compared to **TFT**s, **ATF** does not allow simultaneous events. Compared to **DFT**s, **ATF** is equivalent to the algebra shown in the works reported in [24, 3],

although their algebra has an operator to represent simultaneity, because simultaneity is probabilistically impossible. The inclusion of an operator to represent simultaneity and the proofs of relation of **ATF** to the algebras of **TFT** and **DFT** are left as future work.

The **AADL** is extensible. The work reported in [96] shows an extension to perform dependability analysis through state machines and expressions on fault events and operational modes. Although such an extension captures system behaviour, operational mode activation conditions are expressed in state transitions in combination with an extension of Boolean expressions (not related to order). Our work relates operational modes and fault occurrences order explicitly.

As presented in [52], **TFTs** and **DFTs** structure expressions can be written as formulas in **ATF**. As the root events of **TFTs** and **DFTs** represent operational modes of a system, the **ATF** can be used to associate root events with operational modes, thus allowing the combination of two or more fault trees.

Although the properties of **AL** require that the inner algebra provides tautology and contradiction, and we used **ATF** in the case study, we did not show tautology and contradiction for **ATF**. Instead, we used a law to reduce the **ATF** expression to a Boolean expression. The methodology to check tautology and contradiction in **ATF** is related to expression reduction, which is a future work.

The original expression shown in the case study (Section 6.4) was already H_2 -healthy. The second healthiness condition about completeness uses the concept of undefined value to make any expression H_2 -healthy. Algebraically it is fine, but in practice, the property should be met initially, thus the initial expression is already H_2 -healthy. This property should only be used as an alert to the analyst if it not met initially.

7.1 Future work

The use of Isabelle/HOL gave us a peace of mind to assure our results. Using it, however, requires so much time to get used to the notation, and understand proof mechanisation. All laws shown in Sections 4.1 and 4.2 were proved and are presented in Appendix A. We plan to prove the other theorems related to probabilities, **MCSeq** acceptance criteria verification, and soundness and completeness. Properties of the probability calculation of a formula needs to be proved as well.

Another future work is to relate **ATF** with the algebras shown in [3, 21]. It is important because we can benefit from their results. The main challenge is to define how to express simultaneity in **ATF**, or, at least, how to map from **ATF** to the other algebras.

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Appendix

APPENDIX A – Formal proofs in Isabelle/HOL

In the following we list all theorems and proofs concerning the laws presented in Chapter 4. The complete set of verifiable theory files is available at <<http://www.cin.ufpe.br/~alrd/phd/phd-alrd.zip>> (password: 6Zvq\$5Vyj). We list only those files created in our work. Each theorem, proof or corollary is followed by its own proof.

The theory about lists of distinct elements (distinct lists) is available in [97] (we used the 2015 version that is available with Isabelle/HOL).

This Appendix is organized as follows: (i) Appendix A.1 presents the base lemmas and theorems for sliceable types; (ii) sublists (sliceable distinct lists) are shown in Appendix A.2; (iii) algebraic definitions and laws of the ATF are shown in Appendix A.3, and (iv) proofs using the denotational semantics of sets of distinct lists are shown in Appendix A.4.

A.1 Sliceable

In this section we present a class to express sub-structures for a data type, and laws over such a class. For example, for lists, *sliceable* defines operators and theorems to obtain sublists.

```
class sliceable =
  fixes slice :: "'a ⇒ nat ⇒ nat ⇒ 'a" ("(3_ † _ _)"  [80,80,80] 80)
  fixes size :: "'a ⇒ nat" ("(1#_)" 65)
  fixes empty_inter :: "'a ⇒ 'a ⇒ bool"
  fixes disjoint :: "'a ⇒ bool"

  assumes slice_none: "x † 0..(#x) = x"
  assumes empty_seq_inter [simp]:
    "disjoint x ⟹ c ≤ k ⟹ empty_inter (x † 0..c) (x † k..(#x))"
  assumes size_slice: "size (x † i..j) = max 0 ((min j (size x))-i)"
  assumes slice_slice: "(x † i..j) † a..b = x † (i+a)..(min j (i+b))"
  assumes disjoint_slice_suc:
    "disjoint x ⟹ i ≠ j ⟹ i < (#x) ⟹ j < (#x) ⟹
     x † i..(Suc i) ≠ x † j..(Suc j)"
  assumes disjoint_slice [simp]: "disjoint x ⟹ disjoint (x † i..j)"
  assumes forall_slice_implies_eq: "(#x) = (#y) ∧ (∀ i j. (x † i..j) =
```

```
(y↑i..j)) ←→ (x = y)"
```

```
notation (latex output) slice ("(3_[_.._])" [80,80,80] 80)
```

Teste $x[i..j]$

```
definition slice_right :: "'a::sliceable ⇒ nat ⇒ 'a" ("(2_↑[_.._])" [80,80] 80)
where "slice_right x i = x↑i.."
```

```
notation ("latex") slice_right ("(2_[_.._])" [80,80] 80)
```

```
definition slice_left :: "'a::sliceable ⇒ nat ⇒ 'a" ("(2_↑[_.._])" [80,80] 80)
where "x↑i.. = x↑i..(# x)"
```

```
notation ("latex") slice_left ("(2_[_.._])" [80,80] 80)
```

A.1.1 Disjoint elements and sliceable

```
lemma (in sliceable) slice_right_disjoint[simp]: "disjoint xs ==>
disjoint (slice_right xs i)"
unfolding slice_right_def
by simp
```

The notation for $x[..i]$ is $x[i..]$

```
lemma (in sliceable) slice_left_disjoint[simp]: "disjoint xs ==>
disjoint (xs↑i..)"
unfolding slice_left_def
by simp
```

A.1.2 n-th element in a sliceable

```
abbreviation sliceable_nth :: "'a::sliceable ⇒ nat ⇒ 'a"
where
"sliceable_nth l i ≡ l↑i..(Suc i)"
```

A.1.3 Theorems for sliceable

```
theorem (in sliceable) empty_seq_inter_eq [simp]:
"disjoint x ==> empty_inter (x↑i..) (x↑i..)"
by (simp add: slice_right_def slice_left_def)
```

```

theorem (in sliceable) empty_seq_sliced_inter [simp]:
  "disjoint x ==> b ≤ i ==> j ≤ a ==> i ≤ j ==> a ≤ size x ==>
   empty_inter (x|b..i) (x|j..a)"

proof-
  let ?l = "x|b..a"
  assume lt0: "i ≤ j"
  assume lt1: "j ≤ a"
  assume lt2: "b ≤ i"
  assume lt3: "a ≤ size x"
  assume lt4: "disjoint x"
  have blta: "b ≤ a" using lt0 lt1 lt2 by simp
  have ilter: "i ≤ a" using lt0 lt1 by simp
  hence 2: "empty_inter (?l|0..(i-b)) (?l|(j-b)..(#?l))" using lt4
    using lt0 lt4 disjoint_slice by simp
  hence "empty_inter ((x|b..a)|0..(i-b)) ((x|b..a)|(j-b)..(#?l))" by simp
  hence 3: "empty_inter (x|b..i) ((x|b..a)|(j-b)..(#(x|b..a)))" using ilter lt2
    by (simp add: slice_slice min_absorb2)
  hence 3: "empty_inter (x|b..i) (x|j..a)" using blta lt0 lt2 lt3
    by (auto simp add: size_slice slice_slice min_def)
  thus ?thesis by simp
qed

theorem distinct_slice_lte_inter_empty[simp]:
  "distinct l ==> i ≤ j ==>
   set (take i (drop 0 l))
   ∩ set (take (length l-i) (drop i l)) = {}"
by (simp add: set_take_disj_set_drop_if_distinct )

lemma (in sliceable) size_slice_right_absorb: "#(l|i..) = min i (#l)"
by (simp add: slice_right_def sliceable_class.size_slice)

lemma (in sliceable) size_slice_left_absorb: "#(l|i..) = (#l)-i"
by (simp add: slice_left_def sliceable_class.size_slice)

corollary (in sliceable) slice_right_slice_left_absorb: "(l|i..)|j.. = l|j..i"
unfolding slice_left_def slice_right_def
by (metis (mono_tags, hide_lams) add.left_neutral add.right_neutral max_OL
  min.left_idem size_slice_right_absorb slice_right_def
  sliceable_class.size_slice sliceable_class.slice_none
  sliceable_class.slice_slice)

```

```

corollary (in sliceable) slice_right_slice_left_absorb_empty:
  " $i \leq j \implies (\#((1\dot{\wedge}..i)\dot{\wedge}j..)) = 0$ "
by (simp add: size_slice_left_absorb size_slice_right_absorb)

corollary (in sliceable) slice_left_slice_right_absorb:
  " $(1\dot{\wedge}i..)\dot{\wedge}j = 1\dot{\wedge}i..(i+j)$ "
unfolding slice_left_def slice_right_def
proof -
  have " $(1\dot{\wedge}i..(\#1))\dot{\wedge}0..j = (1\dot{\wedge}0..(\#1))\dot{\wedge}i..(i + j)$ ""
    by (simp add: sliceable_class.slice_slice)
  thus " $(1\dot{\wedge}i..(\#1))\dot{\wedge}0..j = 1\dot{\wedge}i..(i + j)$ ""
    by (simp add: sliceable_class.slice_none)
qed

corollary (in sliceable) slice_right_slice_right_absorb:
  " $(1\dot{\wedge}..i)\dot{\wedge}j = (1\dot{\wedge}..(\min i j))$ "
unfolding slice_left_def slice_right_def
by (simp add: sliceable_class.slice_slice)

corollary (in sliceable) slice_left_slice_left_absorb:
  " $(1\dot{\wedge}i..)\dot{\wedge}j.. = 1\dot{\wedge}(i+j)..$ "
unfolding slice_left_def slice_right_def
by (simp add: sliceable_class.slice_slice sliceable_class.size_slice
  min_absorb1)

corollary (in sliceable) slice_slice_right_absorb:
  " $(1\dot{\wedge}i..j)\dot{\wedge}..b = 1\dot{\wedge}i..(\min j (i+b))$ "
unfolding slice_left_def slice_right_def
by (simp add: add.commute sliceable_class.slice_slice)

corollary (in sliceable) slice_slice_left_absorb:
  " $(1\dot{\wedge}i..j)\dot{\wedge}a.. = 1\dot{\wedge}(i+a)..j$ "
unfolding slice_left_def slice_right_def
by (metis (mono_tags, hide_lams) add.assoc diff_diff_left max_0L
  slice_left_def slice_left_slice_right_absorb slice_right_def
  slice_slice_right_absorb sliceable_class.size_slice
  sliceable_class.slice_none sliceable_class.slice_slice)

corollary (in sliceable) slice_left_slice_absorb:
  " $(1\dot{\wedge}i..)\dot{\wedge}a..b = 1\dot{\wedge}(i+a)..(i+b)$ "
unfolding slice_left_def slice_right_def
by (metis (mono_tags, lifting) slice_left_slice_right_absorb slice_right_def

```

```

slice_right_slice_left_absorb slice_slice_left_absorb
sliceable_class.slice_none)

corollary (in sliceable) slice_right_slice_absorb:
  "(l↑..j)↑a..b = l↑a..(min j b)"
unfolded slice_left_def slice_right_def
by (simp add: sliceable_class.slice_slice)

lemmas (in sliceable) slice_slice_simps =
  slice_left_slice_left_absorb slice_left_slice_right_absorb
  slice_right_slice_left_absorb slice_right_slice_right_absorb slice_slice
  slice_slice_right_absorb slice_slice_left_absorb slice_left_slice_absorb
  slice_right_slice_absorb

lemmas (in sliceable) size_slice_defs =
  size_slice size_slice_left_absorb size_slice_right_absorb

lemma (in sliceable) slice_f_min_neutral:
  "(P (l↑i..(min f k)) ∧ f ≤ k) ↔ (P (l↑i..f) ∧ f ≤ k)"
by linarith

lemma (in sliceable) slice_i_min_neutral:
  "(P (l↑(min i k)..f) ∧ i ≤ k) ↔ (P (l↑i..f) ∧ i ≤ k)"
by linarith

lemma (in sliceable) slice_i_min_neutral_lt:
  "(P (l↑(min k i)..f) ∧ i < k) ↔ (P (l↑i..f) ∧ i < k)"
by linarith

lemma (in sliceable) slice_foral_i_min_neutral:
  "(∀ i f . P (l↑(min i k)..f) ∧ i ≤ k) ↔ (∀ i f . P (l↑i..f) ∧ i ≤ k)"
using not_less by auto

lemma (in sliceable) slice_f_max_neutral:
  "(P (l↑i..(max f k)) ∧ f ≥ k) ↔ (P (l↑i..f) ∧ f ≥ k)"
by (metis max.orderE)

lemma (in sliceable) slice_i_max_neutral:
  "(P (l↑(max i k)..f) ∧ i ≥ k) ↔ (P (l↑i..f) ∧ i ≥ k)"
by (metis max.orderE)

```

```

lemma (in sliceable) empty_slice[simp]: "i ≤ j ==> #(l↑j..i)) = 0"
using local.size_slice by auto

corollary (in sliceable) forall_disjoint_slice_suc:
  "∀ i j . (disjoint x ∧ i ≠ j ∧ i < (#x) ∧ j < (#x)) —>
    (x↑i..(Suc i) ≠ x↑j..(Suc j))"
by (simp add: local.disjoint_slice_suc)

lemma (in sliceable) empty_slice_none:
  "(#x) = 0 ==> #(x↑i..j)) = 0"
by (simp add: size_slice)

corollary (in sliceable) empty_slice_right_none:
  "(#x) = 0 ==> #(x↑..j)) = 0"
by (simp add: slice_right_def sliceable_class.empty_slice_none)

corollary (in sliceable) empty_slice_left_none:
  "(#x) = 0 ==> #(x↑i..)) = 0"
by (simp add: slice_left_def sliceable_class.empty_slice_none)

```

A.2 Sliceable distinct lists

The following is the instantiation of the sliceable class for the dlist type.

```

instantiation dlist :: (type) sliceable
begin

definition
  "l↑i..f = Dlist (take (max 0 (f-i)) (drop i (list_of_dlist l)))"

definition
  "size l = length (list_of_dlist l)"

definition
  "empty_inter l k =
    ((set (list_of_dlist l)) ∩ (set (list_of_dlist k))) = {}"

definition
  "disjoint l = distinct (list_of_dlist l)"

lemma list_of_dlist_slice :

```

```

"list_of_dlist (l↑i..f) = take (max 0 (f-i)) (drop i (list_of_dlist l))"
unfolding slice_dlist_def
by simp

lemma Dlist_slice_inverse :
"list_of_dlist (Dlist (take (max 0 (c-i)) (drop i (list_of_dlist x)))) =
= (take (max 0 (c-i)) (drop i (list_of_dlist x)))"
by simp

lemma Dlist_empty_seq_inter: "c ≤ k ==>
(
set (take c (list_of_dlist x)) ∩
set (drop k (list_of_dlist x))
) = {}"
by (simp add: set_take_disj_set_drop_if_distinct)

lemma Dlist_forall_slice_eq1:
"(∀ i f. (Dlist (take (max 0 (f-i)) (drop i (list_of_dlist l1))) =
Dlist (take (max 0 (f-i)) (drop i (list_of_dlist l2)))) ==>
l1 = l2)"
by (metis (mono_tags, hide_lams) Dlist_list_of_dlist
Sliceable_dlist.list_of_dlist_slice drop_0 drop_take max_0L take_equalityI)

lemma Dlist_forall_slice_eq:
"l1 = l2 <=>
(∀ i f. (Dlist (take (max 0 (f-i)) (drop i (list_of_dlist l1))) =
Dlist (take (max 0 (f-i)) (drop i (list_of_dlist l2)))))"
using Dlist_forall_slice_eq1 by blast

lemma distinct_list_take_1_uniqueness:
"distinct l ==> i ≠ j ==> i < length l ==> j < length l ==>
take 1 (drop i l) ≠ take 1 (drop j l)"
by (simp add: hd_drop_conv_nth nth_eq_iff_index_eq take_Suc)

lemmas list_of_dlist_simps = slice_left_def slice_right_def slice_dlist_def
size_dlist_def disjoint_dlist_def empty_inter_dlist_def Dlist_slice_inverse

instance proof
fix l::'a dlist"
show "l↑0..(#l) = l" by (simp add: dlist_eqI list_of_dlist_slice size_dlist_def)

fix l::'a dlist"

```

```

show "disjoint l" by (simp add: disjoint_dlist_def)
next
fix l::"a dlist" and c::nat and k
assume "c ≤ k"
thus "empty_inter (l↑0..c) (l↑k..(#l))"
by (simp add: size_dlist_def empty_inter_dlist_def
  set_take_disj_set_drop_if_distinct list_of_dlist_slice )
next
fix l::"a dlist" and i and j and a and b
show "size (l↑i..j) = max 0 (min j (#l) - i)"
proof (cases "j ≤ #l")
  case True
  assume "j ≤ #l"
  thus ?thesis
    by (metis (no_types, hide_lams) list_of_dlist_simps(7) size_dlist_def
      drop_take length_drop length_take list_of_dlist_simps(3) max_0L
      min.commute)
  next
  case False
  assume "¬ (j ≤ #l)"
  hence "j > #l" by simp
  thus ?thesis
    by (metis (no_types, lifting) list_of_dlist_simps(3)
      list_of_dlist_simps(7) size_dlist_def length_drop length_take max_0L
      min.commute min_diff)
qed
next
fix l::"a dlist" and i and j and a and b
show "(l↑i..j)↑a..b = l↑(i + a)..(min j (i + b))"
proof -
  have f1: "∀n. max (0::nat) n = n"
    by (meson max_0L)
  hence "take b (take (max 0 (j - i)) (drop i (list_of_dlist l))) = drop i (take
  (i + b) (take j (list_of_dlist l)))"
    by (metis (no_types) diff_add_inverse drop_take)
  hence "take (max 0 (b - a)) (drop a (list_of_dlist (l↑i..j))) = drop a (drop
  i (take (min (i + b) j) (list_of_dlist l)))"
    using f1 by (metis Sliceable_dlist.list_of_dlist_slice drop_take take_take)
  thus ?thesis
    using f1 by (metis (no_types) add.commute drop_drop drop_take list_of_dlist_simps(3)
      min.commute)
qed

```

```

next
fix l::"'a dlist" and i and j
assume "disjoint l" "i ≠ j" "i < (#l)" "j < (#l)"
hence "take 1 (drop i (list_of_dlist l)) ≠
      take 1 (drop j (list_of_dlist l))"
  using distinct_list_take_1_uniqueness size_dlist_def by auto
hence "take (Suc i - i) (drop i (list_of_dlist l)) ≠
      take (Suc j - j) (drop j (list_of_dlist l))"
  by simp
hence "take (max 0 (Suc i - i)) (drop i (list_of_dlist l)) ≠
      take (max 0 (Suc j - j)) (drop j (list_of_dlist l))"
  by simp
thus "l↑i..Suc i ≠ l↑j..Suc j"
by (metis list_of_dlist_slice)
next
fix l1::"'a dlist" and l2::"'a dlist"
show "(#l1) = (#l2) ∧ (∀ i j. l1↑i..j = l2↑i..j) ↔ (l1 = l2)"
  using Dlist_forall_slice_eq
  by (metis Sliceable_dlist.list_of_dlist_slice)
qed

end

```

A.2.1 Properties of sliceable distinct lists

In the following we present lemmas, corollaries and theorems about sliceable distinct lists.

```

abbreviation dlist_nth :: "'a dlist ⇒ nat ⇒ 'a"
where
"alist_nth l i ≡ (list_of_dlist (sliceable_nth l i))!0"

theorem set_slice :
"set (list_of_dlist l) =
 set (list_of_dlist (l↑..i)) ∪ set (list_of_dlist (l↑i..))"
unfolding slice_dlist_def slice_right_def slice_left_def size_dlist_def
apply (simp add: list_of_dlist_inject)
by (metis append_take_drop_id set_append)

theorem take_slice_right: "take n (list_of_dlist l) = list_of_dlist (l↑..n)"
unfolding slice_right_def slice_dlist_def
by (metis Dlist_slice_inverse drop_0 max_0L minus_nat.diff_0)

```

```

theorem slice_right_cons: "distinct (x # xs) ==>
  (Dlist (x # xs))↑..(Suc n) = Dlist (x # (list_of_dlist ((Dlist xs))↑..n)))"
unfolding slice_right_def slice_dlist_def
by (simp add: distinct_remdups_id)

```

```

theorem slice_append:
  " $\forall n. \text{Dlist}((\text{list\_of\_dlist}(l↑..n)) @ (\text{list\_of\_dlist}(l↑n..))) = l$ "
unfolding size_dlist_def slice_left_def slice_right_def
by (simp add: list_of_dlist_inverse list_of_dlist_slice )

```

```

theorem slice_append_mid:
  " $\forall i s e. s \leq i \wedge i \leq e \longrightarrow$ 
    $((\text{list\_of\_dlist}(l↑s..i)) @ (\text{list\_of\_dlist}(l↑i..e))) =$ 
     $\text{list\_of\_dlist}(l↑s..e)$ "
unfolding size_dlist_def slice_left_def slice_right_def list_of_dlist_slice
by (smt Nat.diff_add_assoc2 drop_drop le_add_diff_inverse
      le_add_diff_inverse2 max_0L take_add)

```

```

theorem slice_append_3:
  " $\forall i j. i \leq j \longrightarrow$ 
    $((\text{list\_of\_dlist}(l↑..i)) @$ 
     $(\text{list\_of\_dlist}(l↑i..j)) @ (\text{list\_of\_dlist}(l↑j..)) = \text{list\_of\_dlist } l$ "
unfolding size_dlist_def slice_left_def slice_right_def list_of_dlist_slice
by (metis append_assoc append_take_drop_id drop_0 le_add_diff_inverse
      length_drop max.cobounded2 max_0L minus_nat.diff_0 take_add take_all)

```

```

theorem distinct_slice_lte_inter_empty[simp]:
  " $i \leq j \implies \text{set}(\text{list\_of\_dlist}(l↑..i)) \cap \text{set}(\text{list\_of\_dlist}(l↑j..)) = \{\}$ "
unfolding size_dlist_def slice_left_def slice_right_def
by (simp add: Dlist_empty_seq_inter list_of_dlist_slice )

```

```

corollary distinct_slice_inter_empty [simp]:
  " $\text{set}(\text{list\_of\_dlist}(l↑..i)) \cap \text{set}(\text{list\_of\_dlist}(l↑i..)) = \{\}$ "
by simp

```

```

corollary distinct_slice_lt_inter_empty [simp]:
  " $i < j \implies \text{set}(\text{list\_of\_dlist}(l↑..i)) \cap \text{set}(\text{list\_of\_dlist}(l↑j..)) = \{\}$ "
by simp

```

```

corollary distinct_slice_diff1:
  " $\text{set}(\text{list\_of\_dlist}(l↑..i)) - \text{set}(\text{list\_of\_dlist}(l↑i..)) =$ 

```

```

set (list_of_dlist (l↑..i))"
by (simp add: Diff_triv)

corollary distinct_slice_diff2:
  "set (list_of_dlist (l↑i..)) - set (list_of_dlist (l↑..i)) =
   set (list_of_dlist (l↑i..))"
using distinct_slice_diff1 by fastforce

theorem distinct_in_set_slice1_not_in_slice2:
  "i ≤ j ==>
   x ∈ set (list_of_dlist (l↑..i)) ∧ x ∈ set (list_of_dlist (l↑j..)) ==>
   False"
using distinct_slice_lte_inter_empty by fastforce

corollary distinct_in_set_slice1_implies_not_in_slice2:
  "i ≤ j ==> x ∈ set (list_of_dlist (l↑..i)) ==>
   x ∈ set (list_of_dlist (l↑j..)) ==> False"
by (meson distinct_in_set_slice1_not_in_slice2)

lemma exists_sublist_or_not_sublist [simp]: "∃ i. l↑..i ∈ T ∨ l↑i.. ∉ T"
unfolding slice_right_def slice_left_def
by auto

lemma forall_slice_left_implies_exists [simp]:
  "∀ i . l↑i.. ∈ S ==> ∃ i . l↑(Suc i).. ∈ S"
unfolding slice_right_def slice_left_def
by (simp add: slice_dlist_def)

lemma forall_slice_right_implies_exists [simp]:
  "∀ i . l↑..i ∈ S ==> ∃ i . l↑..(i-1) ∈ S"
unfolding slice_right_def slice_left_def
by auto

lemma take_Suc_Cons_hd_tl: "length l > 0 ==>
  take (Suc n) l = hd l # (take n (tl l))"
apply (induct l)
by auto

```

```

corollary take_Suc_Cons_hd_tl_singleton:
  "length l > 0 ⟹ take (Suc 0) l = [hd l]"
apply (induct l)
by auto

lemma take_drop_suc: "i < length l ⟹ length l > 0 ⟹
  take (max 0 ((Suc i) - i)) (drop i l) = [l!i]"
by (metis (no_types, lifting) Suc_diff_Suc Suc_eq_plus1_left add.commute
  append_eq_append_conv cancel_comm_monoid_add_class.diff_cancel
  hd_drop_conv_nth lessI max_0L numeral_1_eq_Suc_0 numeral_One take_add
  take_hd_drop)

lemma slice_right_take:"l↑..i = Dlist (take i (list_of_dlist l))"
unfolding slice_right_def slice_dlist_def
by auto

lemma slice_left_drop: "l↑i.. = Dlist (drop i (list_of_dlist l))"
unfolding slice_left_def slice_dlist_def size_dlist_def
by auto

lemma take_one_singleton_hd: "l ≠ [] ⟹ take (Suc 0) l = [hd l]"
apply (induct l, simp)
by auto

lemma take_one_singleton_nth: "l ≠ [] ⟹ take (Suc 0) l = [l!0]"
apply (induct l, simp)
by auto

lemma take_one_drop_n_append_singleton_nth:
  "ys ≠ [] ⟹ take 1 (drop (length xs) (xs @ ys)) =
  [(xs @ ys)! (length xs)]"
by (induct xs, auto simp add: take_one_singleton_nth)

lemma append_length_nth_hd: "ys ≠ [] ⟹ [(xs @ ys)! (length xs)] = [hd ys]"
by (induct ys, auto)

lemma take_one_drop_n_singleton_nth: "l ≠ [] ⟹ n < length l ⟹
  take 1 (drop n l) = [l!n]"
proof-
  assume 0: "l ≠ []"
  assume 1: "n < length l"
  obtain xs where "xs = take n l" by simp

```

```

obtain ys where "ys = drop n 1" by simp
have "take 1 (drop n 1) = take 1 (drop (length xs) (xs @ ys))" using 0 1
  by (simp add: 'ys = drop n 1')
also have "... = [(xs @ ys)! (length xs)]" using 0 1
  by (metis 'ys = drop n 1' drop_eq_Nil not_le
       take_one_drop_n_append_singleton_nth)
also have "... = [1!(length xs)]"
  by (simp add: 'xs = take n 1' 'ys = drop n 1')
finally show ?thesis using 0 1
  by (simp add: hd_drop_conv_nth take_one_singleton_hd)
qed

lemma slice_singleton: "(list_of_dlist l) ≠ [] ⟹ i < (#l) ⟹
  list_of_dlist (l↑i..(Suc i)) = [(list_of_dlist l)!i]"
by (metis list_of_dlist_slice length_greater_0_conv size_dlist_def
     take_drop_suc)

lemma slice_right_zero_eq_empty: "list_of_dlist (l↑..0) = []"
by (simp add: slice_right_def slice_dlist_def)

lemma slice_left_size_eq_empty: "list_of_dlist (l↑(#l)..) = []"
by (simp add: slice_left_def slice_dlist_def )

lemma slice_right_singleton_eq_element: "list_of_dlist l ≠ [] ⟹
  list_of_dlist (l↑..1) = [(list_of_dlist l)!0]"
by (metis One_nat_def take_one_singleton_nth take_slice_right)

lemma slice_left_singleton_eq_element: "list_of_dlist l ≠ [] ⟹
  list_of_dlist (l↑((#l)-1)..) = [(list_of_dlist l)!((#l)-1)]"
by (metis (no_types, lifting) Cons_nth_drop_Suc list_of_dlist_slice
     Suc_diff_Suc Suc_leI diff_Suc_eq_diff_pred diff_less drop_0 drop_all
     drop_take length_greater_0_conv max_0L minus_nat.diff_0 size_dlist_def
     slice_left_def slice_none zero_less_one)

lemma dlist_empty_slice[simp]: "i ≤ j ⟹ (l↑j..i) = Dlist []"
by (simp add: slice_dlist_def)

lemma dlist_append_extreme_left:
  "i ≤ j ⟹ list_of_dlist (l↑..j) =
  (list_of_dlist (l↑..i)) @ (list_of_dlist (l↑i..j))"
by (metis list_of_dlist_slice le_add_diff_inverse max_0L take_add
     take_slice_right)

```

```

lemma dlist_append_extreme_right:
  " $i \leq j \implies \text{list\_of\_dlist} (l \upharpoonright i \dots) =$ 
   (\text{list\_of\_dlist} (l \upharpoonright i \dots j)) @ (\text{list\_of\_dlist} (l \upharpoonright j \dots))"
unfolding list_of_dlist_slice slice_left_def slice_right_def
by (metis append_take_drop_id drop_drop le_add_diff_inverse2 length_drop
max.cobounded2 max_0L size_dlist_def take_all)

lemma dlist_disjoint[simp]: "disjoint (l :: 'a dlist)"
by (simp add: disjoint_dlist_def)

lemma dlist_member_suc_nth1:
  " $x \in \text{set} (\text{list\_of\_dlist} (l \upharpoonright i \dots (\text{Suc } i))) \implies x = (\text{list\_of\_dlist} l)!i$ "
proof-
  assume 0: " $x \in \text{set} (\text{list\_of\_dlist} (l \upharpoonright i \dots (\text{Suc } i)))$ "
  obtain rl where 1: "rl = \text{list\_of\_dlist} l" by blast
  hence "x \in \text{set} (\text{take} (\max 0 (\text{Suc } i - i)) (\text{drop } i \text{ rl}))"
    using 0 by (metis list_of_dlist_slice)
  hence "x \in \text{set} (\text{take} 1 (\text{drop } i \text{ rl}))" by simp
  hence "x = rl!i"
    by (metis drop_Nil drop_all empty_iff list.inject list.set(1)
      list.set_cases not_less take_Nil take_one_drop_n_singleton_nth)
  thus ?thesis using 1 by simp
qed

lemma dlist_member_suc_nth2:
  " $i < (\#l) \implies x = (\text{list\_of\_dlist} l)!i \implies$ 
    $x \in \text{set} (\text{list\_of\_dlist} (l \upharpoonright i \dots (\text{Suc } i)))$ "
unfolding size_dlist_def slice_dlist_def
by (metis Dlist_slice_inverse drop_Nil drop_eq_Nil leD length_greater_0_conv
list.set_intros(1) take_drop_suc)

lemma dlist_member_suc_nth: " $i < (\#l) \implies$ 
   $(x = (\text{list\_of\_dlist} l)!i) \longleftrightarrow (x \in \text{set} (\text{list\_of\_dlist} (l \upharpoonright i \dots (\text{Suc } i))))$ "
using dlist_member_suc_nth1 dlist_member_suc_nth2
by fastforce

corollary not_dlist_member_empty[simp]:
  " $\neg \text{Dlist.member} (\text{Dlist.empty}) v$ "
  " $\neg (\text{Dlist.member} (\text{Dlist} []) v)$ "
by (simp add: Dlist.member_def Dlist.empty_def List.member_def)+
```

```

lemma dlist_empty_slice_none: "(Dlist.empty↑i..j) = Dlist.empty"
by (simp add: Dlist.empty_def slice_dlist_def)

corollary dlist_empty_slice_right_none: "(Dlist.empty↑..j) = Dlist.empty"
by (simp add: dlist_empty_slice_none slice_right_def)

corollary dlist_empty_slice_left_none: "(Dlist.empty↑i..) = Dlist.empty"
by (simp add: dlist_empty_slice_none slice_left_def)

lemma dlist_member_slice_empty_none:
  "¬ (Dlist.member (Dlist.empty↑i..j) v)"
by (auto simp add: slice_dlist_def)

corollary dlist_member_slice_right_empty_none[simp]:
  "¬ (Dlist.member (Dlist.empty↑..j) v)"
by (simp add: slice_right_def dlist_empty_slice_none)

corollary dlist_member_slice_left_empty_none[simp]:
  "¬ (Dlist.member (Dlist.empty↑i..) v)"
by (simp add: slice_left_def dlist_empty_slice_none)

lemma dlist_member_slice_member_dlist:
  " $\exists i j. \text{Dlist.member}(\text{dl}↑i..j) v \implies \text{Dlist.member dl v}$ "
unfolding Dlist.member_def List.member_def slice_dlist_def
using in_set_dropD in_set_takeD by fastforce

corollary dlist_member_slice_right_member_dlist:
  " $\exists j. \text{Dlist.member}(\text{dl}↑..j) v \implies \text{Dlist.member dl v}$ "
by (metis dlist_member_slice_member_dlist slice_right_def)

corollary dlist_member_slice_left_member_dlist:
  " $\exists i. \text{Dlist.member}(\text{dl}↑i..) v \implies \text{Dlist.member dl v}$ "
by (metis dlist_member_slice_member_dlist slice_left_def)

lemma sliceable_nth_member1:
  "sliceable_nth dl i = Dlist [v] \implies \text{Dlist.member dl v}"
by (metis Dlist.member_def distinct_remdups_id distinct_singleton
dlist_member_slice_member_dlist in_set_member list.set_intro(1) list_of_dlist_Dlist)

corollary sliceable_nth_member:
  " $\exists i. \text{sliceable\_nth dl i} = Dlist [v] \implies \text{Dlist.member dl v}$ "
by (auto simp add: sliceable_nth_member1)

```

```

lemma sliceable_nth_member_iff:
  "(∃ i. sliceable_nth dl i = Dlist [v]) ↔ Dlist.member dl v"
apply (rule iffI, simp add: sliceable_nth_member)
by (metis Dlist.member_def empty_iff empty_set in_set_conv_nth in_set_member
      list_of_dlist_slice size_dlist_def slice_dlist_def slice_singleton)

```

A.3 Algebra of Temporal Faults

In the following we present the algebraic laws for the [ATF](#).

A.3.1 Basic [ATF](#) operators and tempo_1

```

class temporal_faults_algebra_basic = boolean_algebra +
fixes neutral :: "'a"
fixes xbefore :: "'a ⇒ 'a ⇒ 'a"
fixes tempo1 :: "'a ⇒ bool"
assumes xbefore_bot_1: "xbefore bot a = bot"
assumes xbefore_bot_2: "xbefore a bot = bot"
assumes xbefore_neutral_1: "tempo1 a ⇒ xbefore neutral a = a"
assumes xbefore_neutral_2: "tempo1 a ⇒ xbefore a neutral = a"
assumes xbefore_not_idempotent: "tempo1 a ⇒ xbefore a a = bot"
assumes inf_tempo1: "[tempo1 a; tempo1 b] ⇒ tempo1 (inf a b)"
assumes xbefore_not_sym:
  "[tempo1 a; tempo1 b] ⇒ (xbefore a b) ≤ -(xbefore b a)"

```

A.3.2 Definition of associativity of [XBefore](#)

```

class temporal_faults_algebra_assoc = temporal_faults_algebra_basic +
assumes xbefore_assoc: "[tempo1 a; tempo1 b; tempo1 c] ⇒
  xbefore (xbefore a b) c = xbefore a (xbefore b c)"

```

A.3.3 Equivalences in the [ATF](#) and properties

```

class temporal_faults_algebra_equivs = temporal_faults_algebra_assoc +
fixes independent_events :: "'a ⇒ 'a ⇒ bool"
fixes tempo2 :: "'a ⇒ bool"
fixes tempo3 :: "'a ⇒ bool"
fixes tempo4 :: "'a ⇒ bool"

```

```

assumes xbefore_inf_equiv_bot:
  " $\llbracket \text{tempo1 } a; \text{tempo1 } b \rrbracket \implies \text{inf} (\text{xbefore } a \ b) (\text{xbefore } b \ a) = \text{bot}$ "
assumes xbefore_sup_equiv_inf:
  " $\text{independent\_events } a \ b \implies \llbracket \text{tempo1 } a; \text{tempo1 } b \rrbracket \implies$ 
    $\llbracket \text{tempo2 } a; \text{tempo2 } b \rrbracket \implies \llbracket \text{tempo3 } a; \text{tempo3 } b \rrbracket \implies \llbracket \text{tempo4 } a; \text{tempo4 } b \rrbracket \implies$ 
    $\text{sup} (\text{xbefore } a \ b) (\text{xbefore } b \ a) = \text{inf } a \ b$ "
assumes sup_tempo2: " $\llbracket \text{tempo2 } a; \text{tempo2 } b \rrbracket \implies \text{tempo2} (\text{sup } a \ b)$ "
assumes inf_tempo3: " $\llbracket \text{tempo3 } a; \text{tempo3 } b \rrbracket \implies \text{tempo3} (\text{inf } a \ b)$ "
assumes sup_tempo4: " $\llbracket \text{tempo4 } a; \text{tempo4 } b \rrbracket \implies \text{tempo4} (\text{sup } a \ b)$ "

```

A.3.4 XBefore transitivity

```

class temporal_faults_algebra_trans = temporal_faults_algebra_equivs +
assumes xbefore_trans:
  " $\llbracket \text{tempo1 } a; \text{tempo1 } b; \text{tempo1 } c \rrbracket \implies \llbracket \text{tempo2 } a; \text{tempo2 } b; \text{tempo2 } c \rrbracket \implies$ 
    $\text{less\_eq} (\text{inf} (\text{xbefore } a \ b) (\text{xbefore } b \ c)) (\text{xbefore } a \ c)$ "
assumes inf_xbefore_trans: " $\llbracket \text{tempo1 } b; \text{tempo3 } b \rrbracket \implies$ 
   $\text{inf} (\text{xbefore } a \ b) (\text{xbefore } b \ c) = \text{xbefore} (\text{xbefore } a \ b) \ c$ "

```

A.3.5 Mixed operators in ATF

```

class temporal_faults_algebra_mixed_ops = temporal_faults_algebra_trans +
assumes xbefore_sup_1:
  " $\text{xbefore} (\text{sup } a \ b) \ c = \text{sup} (\text{xbefore } a \ c) (\text{xbefore } b \ c)$ "
assumes xbefore_sup_2:
  " $\text{xbefore } a (\text{sup } b \ c) = \text{sup} (\text{xbefore } a \ b) (\text{xbefore } a \ c)$ "
assumes not_xbefore: "
   $\text{independent\_events } a \ b \implies$ 
   $\llbracket \text{tempo1 } a; \text{tempo1 } b \rrbracket \implies$ 
   $\llbracket \text{tempo2 } a; \text{tempo2 } b \rrbracket \implies$ 
   $\llbracket \text{tempo3 } a; \text{tempo3 } b \rrbracket \implies$ 
   $\llbracket \text{tempo4 } a; \text{tempo4 } b \rrbracket \implies$ 
   $- (\text{xbefore } a \ b) = \text{sup} (\text{sup } (- a) (- b)) (\text{xbefore } b \ a)$ "
assumes inf_xbefore_equiv_sups_xbefore: " $\text{tempo2 } a \implies$ 
   $\text{inf } a (\text{xbefore } b \ c) = \text{sup} (\text{xbefore } (\text{inf } a \ b) \ c) (\text{xbefore } b (\text{inf } a \ c))$ "
assumes not_1_xbefore_equiv: " $\llbracket \text{tempo1 } a; \text{tempo2 } b \rrbracket \implies \text{xbefore } (- a) \ b = b$ "
assumes not_2_xbefore_equiv: " $\llbracket \text{tempo1 } b; \text{tempo2 } a \rrbracket \implies \text{xbefore } a (- b) = a$ ""

class temporal_faults_algebra = temporal_faults_algebra_mixed_ops

```

A.3.6 Theorems in the context of `ATF`

The following theorems are valid for `ATF`. They are valid for any instantiation of the `ATF` class as, for example, for the sets of distinct lists type.

```
context temporal_faults_algebra
begin
```

The following theorem proves Eq. (4.27c).

theorem `xbefore_inf_1`:

```
"independent_events a b ==> [[tempo1 a; tempo1 b]] ==>
[[tempo2 a; tempo2 b]] ==> [[tempo3 a; tempo3 b]] ==> [[tempo4 a; tempo4 b]] ==>
xbefore (inf a b) c =
sup (xbefore (xbefore a b) c) (xbefore (xbefore b a) c)"
```

proof-

```
assume "independent_events a b" "tempo1 a" "tempo1 b"
"tempo2 a" "tempo2 b" "tempo3 a" "tempo3 b" "tempo4 a" "tempo4 b"
hence "xbefore (inf a b) c = xbefore (sup (xbefore a b) (xbefore b a)) c"
by (simp add: xbefore_sup_equiv_inf)
thus ?thesis by (simp add: xbefore_sup_1)
```

qed

The following theorem proves Eq. (4.27d).

theorem `xbefore_inf_2`:

```
"independent_events b c ==> [[tempo1 b; tempo1 c]] ==>
[[tempo2 b; tempo2 c]] ==> [[tempo3 b; tempo3 c]] ==> [[tempo4 b; tempo4 c]] ==>
xbefore a (inf b c) =
sup (xbefore a (xbefore b c)) (xbefore a (xbefore c b))"
```

proof-

```
assume "independent_events b c" "tempo1 b" "tempo1 c" "tempo2 b" "tempo2 c"
"tempo3 b" "tempo3 c" "tempo4 b" "tempo4 c"
hence "xbefore a (inf b c) = xbefore a (sup (xbefore b c) (xbefore c b))"
by (simp add: xbefore_sup_equiv_inf)
thus ?thesis by (simp add: xbefore_sup_2)
```

qed

The following lemma proves Eq. (4.24f).

lemma `xbefore_sup_absorb_1b`:

```
"independent_events a b ==> [[tempo1 a; tempo1 b]] ==>
[[tempo2 a; tempo2 b]] ==> [[tempo3 a; tempo3 b]] ==> [[tempo4 a; tempo4 b]] ==>
sup (xbefore b a) a = a"
by (metis inf_le1 order_trans sup.absorb2 sup.cobounded2
xbefore_sup_equiv_inf)
```

```

lemma xbefore_sup_absorb_2:
  "independent_events a b ==> [[tempo1 a; tempo1 b]] ==>
   [[tempo2 a; tempo2 b]] ==> [[tempo3 a; tempo3 b]] ==> [[tempo4 a; tempo4 b]] ==>
   sup a (xbefore a b) = a"
by (metis dual_order.trans inf.cobounded1 sup.absorb1 sup.cobounded1
    xbefore_sup_equiv_inf)

```

The following corollary proves Eq. (4.24e).

corollary xbefore_sup_absorb_1:

```

"independent_events a b ==> [[tempo1 a; tempo1 b]] ==>
 [[tempo2 a; tempo2 b]] ==> [[tempo3 a; tempo3 b]] ==> [[tempo4 a; tempo4 b]] ==>
 sup (xbefore a b) a = a"

```

proof-

```

assume 0: "independent_events a b" "tempo1 a" "tempo1 b" "tempo2 a"
          "tempo2 b" "tempo3 a" "tempo3 b" "tempo4 a" "tempo4 b"
hence "sup a (xbefore a b) = sup (xbefore a b) a"
      by (simp add: sup.commute)
thus ?thesis using 0 by (simp add: xbefore_sup_absorb_2)
qed

```

corollary xbefore_sup_absorb_2b:

```

"independent_events a b ==> [[tempo1 a; tempo1 b]] ==>
 [[tempo2 a; tempo2 b]] ==> [[tempo3 a; tempo3 b]] ==> [[tempo4 a; tempo4 b]] ==>
 sup a (xbefore b a) = a"

```

proof-

```

assume 0: "independent_events a b" "tempo1 a" "tempo1 b" "tempo2 a"
          "tempo2 b" "tempo3 a" "tempo3 b" "tempo4 a" "tempo4 b"
hence "sup a (xbefore b a) = sup (xbefore b a) a"
      by (simp add: sup.commute)
thus ?thesis using 0 by (simp add: xbefore_sup_absorb_1b)
qed

```

The following corollary proves Eq. (4.27g).

```

theorem xbefore_inf_absorb_1: "independent_events a b ==>
 [[tempo1 a; tempo1 b]] ==>
 [[tempo2 a; tempo2 b]] ==>
 [[tempo3 a; tempo3 b]] ==>
 [[tempo4 a; tempo4 b]] ==>
 inf a (xbefore a b) = xbefore a b"

```

by (simp add: local.inf_absorb2 local.le_iff_sup xbefore_sup_absorb_1)

The following corollary proves Eq. (4.27h).

```
theorem xbefore_inf_absorb_2: "independent_events a b ==>
  [[tempo1 a; tempo1 b]] ==>
  [[tempo2 a; tempo2 b]] ==>
  [[tempo3 a; tempo3 b]] ==>
  [[tempo4 a; tempo4 b]] ==>
  inf a (xbefore b a) = xbefore b a"
by (simp add: local.inf.absorb2 local.sup.absorb_iff1 xbefore_sup_absorb_2b)
```

The following lemma proves Eq. (4.28).

```
lemma inf_xbefore_equiv_sups_xbefore_expanded:
  "independent_events a b ==> independent_events a c ==>
  [[tempo1 a; tempo1 b; tempo1 c]] ==> [[tempo2 a; tempo2 b; tempo2 c]] ==>
  [[tempo3 a; tempo3 b; tempo3 c]] ==> [[tempo4 a; tempo4 b; tempo4 c]] ==>
  inf a (xbefore b c) =
  sup (sup (xbefore (xbefore a b) c)
    (xbefore (xbefore b a) c))
  (xbefore (xbefore b c) a)"
```

proof-

```
assume "independent_events a b" "independent_events a c"
  "tempo1 a" "tempo1 b" "tempo1 c"
  "tempo2 a" "tempo2 b" "tempo2 c"
  "tempo3 a" "tempo3 b" "tempo3 c"
  "tempo4 a" "tempo4 b" "tempo4 c"
hence "inf a (xbefore b c) =
  sup (xbefore (inf a b) c) (xbefore b (inf a c))"
  "xbefore (inf a b) c =
  sup (xbefore (xbefore a b) c) (xbefore (xbefore b a) c)"
  "xbefore b (inf a c) =
  sup (xbefore (xbefore b a) c) (xbefore (xbefore b c) a)"
  by (auto simp add: inf_xbefore_equiv_sups_xbefore xbefore_inf_1
    xbefore_inf_2 xbefore_assoc)
thus ?thesis by (simp add: sup.assoc)
qed
```

corollary inf_xbefore_equiv_sups_xbefore_1:

```
"independent_events a b ==> independent_events a c ==>
  [[tempo1 a; tempo1 b; tempo1 c]] ==> [[tempo2 a; tempo2 b; tempo2 c]] ==>
  [[tempo3 a; tempo3 b; tempo3 c]] ==> [[tempo4 a; tempo4 b; tempo4 c]] ==>
  inf a (xbefore b c) =
  sup (sup (xbefore (xbefore a b) c) (xbefore (xbefore b a) c))
  (xbefore (xbefore b c) a)"
```

```
by (simp add: inf_xbefore_equiv_sup_xbefore_expanded)
```

The following lemma proves Eq. (4.29d).

```
lemma xbefore_sup_compl_inf_absorb1:
  "independent_events a b ==> [[tempo1 a; tempo1 b]] ==>
   [[tempo2 a; tempo2 b]] ==> [[tempo3 a; tempo3 b]] ==> [[tempo4 a; tempo4 b]] ==>
   sup (inf a (-b)) (xbefore a b) = inf a (- (xbefore b a))"
proof -
  assume a1: "independent_events a b"
  assume a2: "tempo1 a"
  assume a3: "tempo1 b"
  assume a4: "tempo2 a"
  assume a5: "tempo2 b"
  assume a6: "tempo3 a"
  assume a7: "tempo3 b"
  assume a8: "tempo4 a"
  assume a9: "tempo4 b"
  then have f10: "- xbefore a b = sup (sup (- a) (- b)) (xbefore b a)"
    using a8 a7 a6 a5 a4 a3 a2 a1 by (meson local.not_xbefore)
  have f11: "∀a aa ab. inf (a::'a) (sup aa ab) = sup (inf a aa) (inf a ab)"
    using local.distrib_imp2 local.sup_inf_distrib1 by force
  then have f12: "sup bot (xbefore b a) = inf b (sup (- b) (xbefore b a))"
    using a7 a3 by (metis local.inf_compl_bot local.inf_xbefore_trans local.xbefore_neutr)
  have f13: "inf (sup (- a) (- (- b))) (sup (- a) (- b)) = sup (- a) (inf b (- b))"
    using local.double_compl local.sup_inf_distrib1 by presburger
  have f14: "inf a (xbefore b a) = xbefore b a"
    using a9 a8 a7 a6 a5 a4 a3 a2 a1 by (meson xbefore_inf_absorb_2)
  have f15: "sup (sup (inf (sup (- a) (- b)) (- a)) (inf (xbefore b a) (- a))) bot
  = sup (- a) (inf b (- b)))"
    using f10 a9 a8 a7 a6 a5 a4 a3 a2 a1 by (metis (no_types) local.compl_sup local.inf_compl_inf_sup_distrib2 xbefore_sup_absorb_1)
  have "inf a (- a) = sup (inf (xbefore b a) (- a)) bot"
    using f14 f11 by (metis (no_types) local.compl_inf local.inf_compl_bot)
  then have "sup (- sup (- a) (- (- b))) (- sup (- a) (- b)) = - inf (sup (sup (- a) (- b)) a) (- a))"
    using f15 f13 by (metis (full_types) local.compl_inf local.inf_sup_distrib2 local.sup_assoc)
  then have "sup (- sup (- a) (- (- b))) (- sup (- a) (- b)) = a"
    by (simp add: local.sup_assoc)
  then show ?thesis
    using f13 f12 f10 by (metis (no_types) local.compl_inf local.compl_sup local.double_compl_inf_sup_distrib2 local.inf_compl_bot local.sup_assoc local.sup_inf_distrib1)
```

```
qed
```

```
end
```

```
end
```

A.4 Denotational semantics for ATF

In the following we present the denotation semantics for **ATF** in terms of sets of distinct lists.

A.4.1 Formula: distinct lists

The definition of a formula in the **ATF** is a set of sets of distinct lists (dlist).

```
typedef 'a formula = "UNIV::'a dlist set set" by simp
```

A.4.1.1 Formula as Boolean algebra

In the following we instantiate the formula as a Boolean algebra and prove that Boolean operators are valid.

```
instantiation formula :: (type) boolean_algebra
begin
```

definition

$$"x \sqcap y = Abs_formula (Rep_formula x \cap Rep_formula y)"$$

definition

$$"x \sqcup y = Abs_formula (Rep_formula x \cup Rep_formula y)"$$

definition

$$"\top = Abs_formula UNIV"$$

definition

$$"\perp = Abs_formula \{\}"$$

definition

$$"x \leq y \longleftrightarrow Rep_formula x \subseteq Rep_formula y"$$

definition

```

"x < y  $\longleftrightarrow$  Rep_formula x ⊂ Rep_formula y"

definition
"- x = Abs_formula (- (Rep_formula x))"

definition
"x - y = Abs_formula (Rep_formula x - Rep_formula y)"

lemma Rep_formula_inf:
"Rep_formula (x ∩ y) = Rep_formula x ∩ Rep_formula y"
unfolding inf_formula_def
by (simp add: Abs_formula_inverse Rep_formula)

lemma Rep_formula_sup:
"Rep_formula (x ∪ y) = Rep_formula x ∪ Rep_formula y"
unfolding sup_formula_def
by (simp add: Abs_formula_inverse Rep_formula)

lemma Rep_formula_top[simp]: "Rep_formula ⊤ = UNIV"
unfolding top_formula_def
by (simp add: Abs_formula_inverse)

lemma Rep_formula_bot[simp]: "Rep_formula ⊥ = {}"
unfolding bot_formula_def
by (simp add: Abs_formula_inverse)

lemma Rep_formula_compl: "Rep_formula (- x) = - Rep_formula x"
unfolding uminus_formula_def
by (simp add: Abs_formula_inverse Rep_formula)

lemma Rep_formula_diff:
"Rep_formula (x - y) = Rep_formula x - Rep_formula y"
unfolding minus_formula_def
by (simp add: Abs_formula_inverse Rep_formula)

lemmas eq_formula_iff = Rep_formula_inject [symmetric]

lemmas Rep_formula_boolean_algebra_simps =
less_eq_formula_def less_formula_def eq_formula_iff
Rep_formula_sup Rep_formula_inf Rep_formula_top Rep_formula_bot
Rep_formula_compl Rep_formula_diff

```

instance proof

qed (*unfold Rep_formula_boolean_algebra_simps*, *auto*)

The instantiation and this proof shows that *ATF* is a Boolean algebra as shown in Eqs. (4.11a) to (4.11g).

end

A.4.1.2 Tempo properties

In this section we define the tempo properties.

Tempo1: disjoint split

definition *dlist_tempo1* :: "('a dlist ⇒ bool) ⇒ bool"

where

"*dlist_tempo1 S* ≡ ∀ i j l. i ≤ j → ¬ ((S (l↑..i)) ∧ S (l↑j..))"

Tempo2: belonging iff

definition *dlist_tempo2* :: "('a dlist ⇒ bool) ⇒ bool"

where

"*dlist_tempo2 S* ≡ ∀ i l. S l ↔ (S (l↑..i)) ∨ S (l↑i..))"

definition *dlist_tempo3* :: "('a dlist ⇒ bool) ⇒ bool"

where

"*dlist_tempo3 S* ≡ ∀ i j l. j < i → (S (l↑j..i)) ↔ (S (l↑..i)) ∧ S (l↑j..))"

definition *dlist_tempo4* :: "('a dlist ⇒ bool) ⇒ bool"

where

"*dlist_tempo4 S* ≡ ∀ l. S l ↔ (∃ i. S (l↑i..(Suc i)))"

definition *dlist_tempo5* :: "('a dlist ⇒ bool) ⇒ bool"

where

"*dlist_tempo5 S* ≡ ∀ i j l. (i ≠ j ∧ i < (#l) ∧ j < (#l)) → ¬(S (l↑i..(Suc i)) ∧ S (l↑j..(Suc j)))"

definition *dlist_tempo6* :: "('a dlist ⇒ bool) ⇒ bool"

where

"*dlist_tempo6 S* ≡ ∀ l. (∀ i j. ¬ S (l↑i..j)) ↔ ¬ S l"

definition *dlist_tempo7* :: "('a dlist ⇒ bool) ⇒ bool"

where

```
"dlist_tempo7 S ≡ ∀l. (Ǝ i j. i < j ∧ S (l↑i..j)) ↔ S l"
```

definition *dlist_tempo* :: "('a dlist ⇒ bool) ⇒ bool"

where

```
"dlist_tempo S ≡ dlist_tempo1 S ∧ dlist_tempo2 S ∧
dlist_tempo3 S ∧ dlist_tempo5 S ∧ dlist_tempo4 S ∧ dlist_tempo6 S ∧
dlist_tempo7 S"
```

lemmas *tempo_defs* = *dlist_tempo_def* *dlist_tempo1_def* *dlist_tempo2_def*
dlist_tempo3_def *dlist_tempo5_def* *dlist_tempo4_def* *dlist_tempo6_def*
dlist_tempo7_def

lemma *dlist_tempo_1_no_gap*:

```
"dlist_tempo1 S ⇒ ∀i l. ¬ ((S (l↑..i) ∧ S (l↑i..)))"
```

unfolding *dlist_tempo1_def*

by *auto*

corollary *dlist_tempo_1_no_gap_append*:

```
"dlist_tempo1 S ⇒
∀zs xs ys. list_of_dlist zs = list_of_dlist xs @ list_of_dlist ys →
¬ ((S xs ∧ S ys))"
```

using *dlist_tempo_1_no_gap*

by (*metis Dlist.list_of_dlist append_eq_conv_conj slice_left_drop*
take_slice_right)

A.4.1.3 Tempo properties for list member

We use the naming convention of variable, but in fact, a variable is equivalent to a list membership: *var a = {xs | a ∈ list_of_dlist xs}*.

lemma *dlist_tempo1_member*: "dlist_tempo1 (λxs. Dlist.member xs a)"

unfolding *dlist_tempo1_def* *Dlist.member_def* *List.member_def*

by (*meson distinct_in_set_slice1_not_in_slice2*)

lemma *dlist_tempo2_member*: "dlist_tempo2 (λxs. Dlist.member xs a)"

unfolding *dlist_tempo2_def* *Dlist.member_def* *List.member_def*

by (*metis (no_types, lifting) Un_iff set_slice*)

lemma *dlist_tempo3_member*: "dlist_tempo3 (λxs. Dlist.member xs a)"

unfolding *dlist_tempo3_def* *Dlist.member_def* *List.member_def*

by (*metis DiffD2 Un_iff distinct_slice_diff2 dlist_append_extreme_left*
dlist_append_extreme_right less_imp_le_nat set_append)

```

lemma dlist_tempo5_member: "dlist_tempo5 (λxs. Dlist.member xs a)"
  unfolding dlist_tempo5_def Dlist.member_def List.member_def
  by (metis Dlist_list_of_dlist Suc_leI disjoint_dlist_def disjoint_slice_suc
       distinct_list_of_dlist dlist_empty_slice dlist_member_suc_nth1 empty_slice
       less_Suc_eq_0_disj not_less_eq slice_singleton)

lemma dlist_tempo4_member: "dlist_tempo4 (λxs. Dlist.member xs a)"
  unfolding dlist_tempo4_def Dlist.member_def List.member_def
  by (metis dlist_member_suc_nth in_set_conv_nth in_set_dropD in_set_takeD
       list_of_dlist_Dlist set_remdups size_dlist_def slice_dlist_def)

lemma dlist_tempo6_member: "dlist_tempo6 (λxs. Dlist.member xs a)"
  unfolding dlist_tempo6_def Dlist.member_def List.member_def
  by (metis append_Nil in_set_conv_decomp in_set_conv_nth in_set_dropD
       in_set_takeD length_pos_if_in_set list_of_dlist_slice take_drop_suc)

lemma dlist_tempo7_member: "dlist_tempo7 (λxs. Dlist.member xs a)"
  unfolding dlist_tempo7_def Dlist.member_def List.member_def
  by (metis Un_iff dlist_append_extreme_left dlist_member_suc_nth2
       in_set_conv_nth lessI less_imp_le_nat set_append set_slice size_dlist_def)

theorem dlist_tempo_member: "dlist_tempo (λxs. Dlist.member xs a)"
  unfolding dlist_tempo_def
  by (simp add: dlist_tempo1_member dlist_tempo2_member dlist_tempo3_member
             dlist_tempo5_member dlist_tempo4_member dlist_tempo6_member
             dlist_tempo7_member)

```

A.4.1.4 Tempo properties for other operators

```

lemma dlist_tempo1_inf: "⟦dlist_tempo1 a; dlist_tempo1 b⟧ ⟹
  dlist_tempo1 (λzs. a zs ∧ b zs)"
  unfolding dlist_tempo1_def
  by simp

lemma dlist_tempo3_inf: "⟦dlist_tempo3 a; dlist_tempo3 b⟧ ⟹
  dlist_tempo3 (λzs. a zs ∧ b zs)"
  unfolding dlist_tempo3_def
  by auto

lemma dlist_tempo2_sup: "⟦dlist_tempo2 a; dlist_tempo2 b⟧ ⟹

```

```

dlist_tempo2 ( $\lambda z. a \ z \vee b \ z$ )"
unfolding dlist_tempo2_def
by auto

lemma dlist_tempo4_sup: " $\llbracket dlist\_tempo4 \ a; dlist\_tempo4 \ b \rrbracket \implies$ 
dlist_tempo4 ( $\lambda z. a \ z \vee b \ z$ )"
unfolding dlist_tempo4_def
by blast

```

A.4.2 XBefore of distinct lists

```

definition dlist_xbefore :: "('a dlist  $\Rightarrow$  bool)  $\Rightarrow$  ('a dlist  $\Rightarrow$  bool)  $\Rightarrow$ 
'a dlist  $\Rightarrow$  bool"
where
"dlist_xbefore a b xs \equiv \exists i. a (xs\dot{+}..i) \wedge b (xs\dot{+}i..)"

```

A.4.2.1 XBefore and temporal properties

```

lemma dlist_tempo1_xbefore: " $\llbracket dlist\_tempo1 \ a; dlist\_tempo1 \ b \rrbracket \implies$ 
dlist_tempo1 (dlist_xbefore a b)"
unfolding dlist_tempo1_def dlist_xbefore_def slice_slice_simps
by (smt le_add1 min.absorb2 min.cobounded1 slice_right_slice_left_absorb
slice_right_slice_right_absorb)

```

A.4.2.2 XBefore and appending

```

lemma Rep_slice_append:
"list_of_dlist zs = (list_of_dlist (zs\dot{+}..i)) @ (list_of_dlist (zs\dot{+}i..))"
by (metis distinct_append distinct_list_of_dlist distinct_slice_inter_empty
list_of_dlist_Dlist remdups_id_iff_distinct slice_append)

lemma dlist_xbefore_append:
"dlist_xbefore a b zs \leftrightarrow
(\exists xs ys. set (list_of_dlist xs) \cap set (list_of_dlist ys) =
{}) \wedge a \in xs \wedge b \in ys \wedge
list_of_dlist zs = ((list_of_dlist xs) @ (list_of_dlist ys)))"
unfolding dlist_xbefore_def
by (metis Rep_slice_append append_Nil2 append_eq_conv_conj
distinct_slice_inter_empty dlist_xbefore_def drop_take_max_OL
size_dlist_def slice_append slice_dlist_def slice_left_def slice_right_def
take_slice_right)

```

A.4.2.3 XBefore , bot, top and idempotency

```
lemma dlist_xbefore_bot_1: "dlist_xbefore (\lambda xs. False) b zs = False"
unfolding dlist_xbefore_def
by simp
```

```
corollary dlistset_xbefore_bot_1:
  "Collect (dlist_xbefore (\lambda xs. False) b) = {}"
by (simp add: dlist_xbefore_bot_1)
```

```
lemma dlist_xbefore_bot_2: "dlist_xbefore a (\lambda xs. False) zs = False"
unfolding dlist_xbefore_def
by simp
```

```
lemma dlistset_xbefore_bot_2:
  "Collect (dlist_xbefore a (\lambda xs. False)) = {}"
by (simp add: dlist_xbefore_bot_2)
```

```
lemma dlist_xbefore_idem:
  "dlist_tempo1 a \implies dlist_xbefore a a zs = False"
unfolding dlist_xbefore_def dlist_tempo1_def
by blast
```

```
lemma dlistset_xbefore_idem:
  "dlist_tempo1 a \implies Collect (dlist_xbefore a a) = {}"
by (simp add: dlist_xbefore_idem)
```

```
lemma dlist_xbefore_implies_idem:
  "\forall xs. b xs \longrightarrow a xs \implies dlist_tempo1 a \implies dlist_xbefore a b zs = False"
unfolding dlist_tempo1_def dlist_xbefore_def
by blast
```

A.4.2.4 XBefore neutral

```
lemma dlist_xbefore_neutral_1:
  "dlist_tempo1 a \implies dlist_xbefore (\lambda xs. xs = dlist_of_list []) a zs = a zs"
by (metis (full_types) Dlist_list_of_dlist Rep_slice_append append.simps(1)
  dlist_of_list dlist_xbefore_def take_0 take_slice_right)
```

```
corollary dlistset_xbefore_neutral_1:
  "dlist_tempo1 a \implies Collect (dlist_xbefore (\lambda xs. xs = Dlist []) a) = Collect a"
```

```

using dlist_xbefore_neutral_1 by auto

lemma dlist_xbefore_neutral_2:
  "dlist_tempo1 a ==> dlist_xbefore a (λxs. xs = Dlist []) zs = a zs"
  by (smt Dlist_list_of_dlist append_Nil2 distinct_append distinct_list_of_dlist dlist_of_1

  dlist_xbefore_append list_of_dlist_empty)

corollary dlistset_xbefore_neutral_2:
  "dlist_tempo1 a ==> Collect (dlist_xbefore a (λxs. xs = Dlist [])) = Collect a"
  using dlist_xbefore_neutral_2 by auto

```

A.4.2.5 XBefore associativity

```

theorem dlist_xbefore_assoc1:
  "dlist_tempo1 S ==> dlist_tempo1 T ==> dlist_tempo1 U ==>
   (dlist_xbefore (dlist_xbefore S T) U zs) <→
   (dlist_xbefore S (dlist_xbefore T U) zs)"
  unfolding dlist_xbefore_def slice_slice_simps dlist_tempo_def
  apply auto
  apply (metis diff_is_0_eq less_imp_le max_0L min_def not_le
         ordered_cancel_comm_monoid_diff_class.le_iff_add slice_dlist_def
         take_eq_Nil)
  by (metis le_add1 min.absorb2)

```

```

corollary dlist_xbefore_assoc:
  "dlist_tempo1 S ==> dlist_tempo1 T ==> dlist_tempo1 U ==>
   (dlist_xbefore (dlist_xbefore S T) U) =
   (dlist_xbefore S (dlist_xbefore T U))"
  using dlist_xbefore_assoc1 by blast

```

```

corollary dlistset_xbefore_assoc:
  "dlist_tempo1 S ==> dlist_tempo1 T ==> dlist_tempo1 U ==>
   Collect (dlist_xbefore (dlist_xbefore S T) U) =
   Collect (dlist_xbefore S (dlist_xbefore T U))"
  by (simp add: dlist_xbefore_assoc)

```

A.4.2.6 XBefore equivalences

```

lemma dlist_tempo1_le_uniqueness:
  "dlist_tempo1 S ==> S (l†..i) ==> i ≤ j ==> ¬ S (l†j..)" and
  "dlist_tempo1 S ==> S (l†j..) ==> i ≤ j ==> ¬ S (l†..i)"
  unfolding dlist_tempo1_def

```

by auto

lemma *dlist_xbefore_not_sym*:
 "dlist_tempo1 S \Rightarrow dlist_tempo1 T \Rightarrow dlist_xbefore S T xs \Rightarrow
 dlist_xbefore T S xs \Rightarrow False"
 by (metis dlist_xbefore_def le_cases dlist_tempo1_le_uniqueness)

corollary *dlist_xbefore_and*:

"dlist_tempo1 S \Rightarrow dlist_tempo1 T \Rightarrow
 ((dlist_xbefore S T zs) \wedge (dlist_xbefore T S zs)) = False"
 using *dlist_xbefore_not_sym* by blast

corollary *dlistset_xbefore_and*:

"dlist_tempo1 S \Rightarrow dlist_tempo1 T \Rightarrow
 (Collect (dlist_xbefore S T)) \cap (Collect (dlist_xbefore T S)) = {}"
 using *dlist_xbefore_and*
 by auto

lemma *dlist_tempo2_left_absorb*: "dlist_tempo2 S \Rightarrow S (1*i*..) \Rightarrow S 1"
 unfolding *dlist_tempo2_def*
 by auto

lemma *dlist_tempo2_right_absorb*: "dlist_tempo2 S \Rightarrow S (1..*i*) \Rightarrow S 1"
 unfolding *dlist_tempo2_def*
 by auto

lemma *dlist_xbefore_implies_member1*[simp]:
 "dlist_tempo2 S \Rightarrow dlist_xbefore S T 1 \Rightarrow S 1"
 by (meson dlist_xbefore_def dlist_tempo2_right_absorb)

lemma *dlist_xbefore_implies_member2*[simp]:
 "dlist_tempo2 T \Rightarrow dlist_xbefore S T 1 \Rightarrow T 1"
 by (meson dlist_xbefore_def dlist_tempo2_left_absorb)

lemma *dlist_xbefore_or1*:
 "dlist_tempo2 S \Rightarrow dlist_tempo2 T \Rightarrow
 dlist_xbefore S T 1 \vee dlist_xbefore T S 1 \Rightarrow S 1 \wedge T 1"
 using *dlist_xbefore_implies_member1* *dlist_xbefore_implies_member2* by blast

definition *dlist_independent_events* ::

```

"(’a dlist ⇒ bool) ⇒ (’a dlist ⇒ bool) ⇒ bool"
where
"alist_independent_events S T ≡
(∀ i l. ¬ (S (l↑i..(Suc i)) ∧ T (l↑i..(Suc i))))"

lemma alist_independent_events_member: "a ≠ b ⇒
alist_independent_events (λ dl. Dlist.member dl a) (λ dl. Dlist.member dl b)"
apply (simp add: alist_independent_events_def Dlist.member_def List.member_def)
by (metis alist_member_suc_nth1)

lemma alist_and_split9:
"alist_independent_events S T ⇒
alist_tempo2 S ⇒ alist_tempo2 T ⇒
alist_tempo3 S ⇒ alist_tempo3 T ⇒
alist_tempo4 S ⇒ alist_tempo4 T ⇒
S l ∧ T l ↔ (∃ i j. i ≤ j ∧
((S (l↑..i) ∧ T (l↑j..)) ∨ (S (l↑j..) ∧ T (l↑..i))))"
unfolding alist_independent_events_def
alist_tempo2_def alist_tempo3_def alist_tempo4_def
by (metis le_refl not_less not_less_eq_eq)

lemma alist_tempo_equiv_xor:
"alist_tempo1 S ⇒ alist_tempo2 S ⇒
∀ l. S l ↔ (∀ i. (S (l↑..i) ∧ ¬ S (l↑i..)) ∨ (¬ S (l↑..i) ∧ S (l↑i..)))"
unfolding tempo_defs
by (meson order_refl)

corollary alist_tempo_equiv_not_eq: "alist_tempo1 S ⇒ alist_tempo2 S ⇒
∀ l. S l ↔ (∀ i. S (l↑..i) ≠ S (l↑i..))"
using alist_tempo_equiv_xor
by auto

lemma alists_xbefore_or2:
"alist_independent_events S T ⇒
alist_tempo1 S ⇒ alist_tempo1 T ⇒
alist_tempo2 S ⇒ alist_tempo2 T ⇒
alist_tempo3 S ⇒ alist_tempo3 T ⇒

```

```
dlist_tempo4 S ==> dlist_tempo4 T ==>
S 1 ∧ T 1 ==> dlist_xbefore S T 1 ∨ dlist_xbefore T S 1"
unfolding dlist_xbefore_def dlist_tempo_def
by (metis dlist_and_split9 dlist_tempo_equiv_not_eq
dlist_tempo1_le_uniqueness)
```

theorem *dlist_xbefore_or_one_list*:

```
"dlist_independent_events S T ==>
dlist_tempo1 S ==> dlist_tempo1 T ==>
dlist_tempo2 S ==> dlist_tempo2 T ==>
dlist_tempo3 S ==> dlist_tempo3 T ==>
dlist_tempo4 S ==> dlist_tempo4 T ==>
dlist_xbefore S T 1 ∨ dlist_xbefore T S 1 ↔ S 1 ∧ T 1"
using dlist_xbefore_or1 dlists_xbefore_or2 dlist_tempo_def
by blast
```

corollary *dlist_xbefore_or*:

```
"dlist_independent_events S T ==>
dlist_tempo1 S ==> dlist_tempo1 T ==>
dlist_tempo2 S ==> dlist_tempo2 T ==>
dlist_tempo3 S ==> dlist_tempo3 T ==>
dlist_tempo4 S ==> dlist_tempo4 T ==>
(λzs. (dlist_xbefore S T zs) ∨ (dlist_xbefore T S zs)) =
(λzs. S zs ∧ T zs)"
using dlist_xbefore_or_one_list
by blast
```

corollary *dlistset_xbefore_or*:

```
"dlist_independent_events S T ==>
dlist_tempo1 S ==> dlist_tempo1 T ==>
dlist_tempo2 S ==> dlist_tempo2 T ==>
dlist_tempo3 S ==> dlist_tempo3 T ==>
dlist_tempo4 S ==> dlist_tempo4 T ==>
(Collect (dlist_xbefore S T)) ∪ (Collect (dlist_xbefore T S)) =
Collect S ∩ Collect T"
using dlist_xbefore_or
by (smt Collect_cong Collect_conj_eq Collect_disj_eq)
```

A.4.2.7 XBefore transitivity

theorem *dlist_xbefore_trans*: "
 $\llbracket \text{dlist_tempo1 } a; \text{dlist_tempo1 } b; \text{dlist_tempo1 } c \rrbracket \Rightarrow$

```

 $\llbracket dlist\_tempo2\ a; dlist\_tempo2\ b; dlist\_tempo2\ c \rrbracket \implies$ 
 $dlist\_xbefore\ a\ b\ zs \wedge dlist\_xbefore\ b\ c\ zs \implies$ 
 $dlist\_xbefore\ a\ c\ zs"$ 
using dlist_xbefore_not_sym
by (metis dlist_tempo2_def dlist_xbefore_def)

corollary dlistset_xbefore_trans: "
 $\llbracket dlist\_tempo1\ a; dlist\_tempo1\ b; dlist\_tempo1\ c \rrbracket \implies$ 
 $\llbracket dlist\_tempo2\ a; dlist\_tempo2\ b; dlist\_tempo2\ c \rrbracket \implies$ 
 $(Collect\ (dlist\_xbefore\ a\ b) \cap Collect\ (dlist\_xbefore\ b\ c)) \subseteq$ 
 $Collect\ (dlist\_xbefore\ a\ c)"$ 
using dlist_xbefore_trans
by auto

```

A.4.2.8 Boolean operators mixed with XBefore

```

theorem mixed_dlist_xbefore_or1: "
 $dlist\_xbefore\ (\lambda xs.\ a\ xs \vee b\ xs)\ c\ zs =$ 
 $((dlist\_xbefore\ a\ c\ zs) \vee (dlist\_xbefore\ b\ c\ zs))"$ 
unfolding dlist_xbefore_def by auto

corollary mixed_dlistset_xbefore_or1: "
 $Collect\ (dlist\_xbefore\ (\lambda xs.\ a\ xs \vee b\ xs)\ c) =$ 
 $Collect\ (dlist\_xbefore\ a\ c) \cup Collect\ (dlist\_xbefore\ b\ c)"$ 
proof-
  have "Collect\ (\lambda zs.\ (dlist\_xbefore\ a\ c\ zs) \vee (dlist\_xbefore\ b\ c\ zs)) ="
     $(Collect\ (dlist\_xbefore\ a\ c) \cup Collect\ (dlist\_xbefore\ b\ c))"$ 
  by (simp add: Collect_disj_eq)
  thus ?thesis using mixed_dlist_xbefore_or1 by blast
qed

theorem mixed_dlist_xbefore_or2: "
 $dlist\_xbefore\ a\ (\lambda xs.\ b\ xs \vee c\ xs)\ zs =$ 
 $((dlist\_xbefore\ a\ b\ zs) \vee (dlist\_xbefore\ a\ c\ zs))"$ 
unfolding dlist_xbefore_def by auto

corollary mixed_dlistset_xbefore_or2: "
 $Collect\ (dlist\_xbefore\ a\ (\lambda xs.\ b\ xs \vee c\ xs)) =$ 
 $Collect\ (dlist\_xbefore\ a\ b) \cup Collect\ (dlist\_xbefore\ a\ c)"$ 
proof-
  have "Collect\ (\lambda zs.\ (dlist\_xbefore\ a\ b\ zs) \vee (dlist\_xbefore\ a\ c\ zs)) ="
     $Collect\ (dlist\_xbefore\ a\ b) \cup Collect\ (dlist\_xbefore\ a\ c)"$ 

```

```

by (simp add: Collect_disj_eq)
thus ?thesis using mixed_dlist_xbefore_or2 by blast
qed

lemma and_dlist_xbefore_equiv_or_dlist_xbefore:
  "dlist_tempo2 a ==>
   (a zs ∧ dlist_xbefore b c zs) <=>
   (dlist_xbefore (λ xs. a xs ∧ b xs) c zs ∨
    dlist_xbefore b (λ xs. a xs ∧ c xs) zs)"
proof-
  assume "dlist_tempo2 a"
  hence 0: "∀ i xs. a xs <=> (a (xs↑..i) ∨ a (xs↑i..))"
    using dlist_tempo2_def by auto
  have "a zs ∧ dlist_xbefore b c zs <=>
    a zs ∧ (∃ i. b (zs↑..i) ∧ c (zs↑i..))"
    by (auto simp add: dlist_xbefore_def)
  thus ?thesis using 0 by (auto simp add: dlist_xbefore_def)
qed

corollary and_dlistset_xbefore_equiv_or_dlistset_xbefore:
  "dlist_tempo2 a ==>
   ((Collect a) ∩ (Collect (dlist_xbefore b c))) =
   (Collect (dlist_xbefore (λ xs. a xs ∧ b xs) c) ∪
    Collect (dlist_xbefore b (λ xs. a xs ∧ c xs)))"
by (smt Collect_cong Collect_conj_eq Collect_disj_eq dlist_tempo2_def
     dlist_xbefore_def)

lemma dlist_xbefore_implies_not_sym_dlist_xbefore: "
  [dlist_tempo1 a; dlist_tempo1 b] ==>
  dlist_xbefore a b zs ==> ¬ dlist_xbefore b a zs"
unfolding dlist_xbefore_def dlist_tempo1_def
by (meson nat_le_linear)

corollary dlistset_xbefore_implies_not_sym_dlistset_xbefore:
  "[dlist_tempo1 a; dlist_tempo1 b] ==>
   Collect (dlist_xbefore a b) ⊆ - Collect (dlist_xbefore b a))"
using dlist_xbefore_implies_not_sym_dlist_xbefore
by (metis (mono_tags, lifting) CollectD ComplI subsetI)

theorem mixed_not_dlist_xbefore: "dlist_independent_events a b ==>
  [dlist_tempo1 a; dlist_tempo1 b] ==>
  [dlist_tempo2 a; dlist_tempo2 b] ==>

```

```

[dlist_tempo3 a; dlist_tempo3 b] ==>
[dlist_tempo4 a; dlist_tempo4 b] ==>
(¬ (dlist_xbefore a b zs)) =
((¬ a zs) ∨ (¬ b zs) ∨ (dlist_xbefore b a zs))"
using dlist_xbefore_implies_not_sym_dlist_xbefore dlist_xbefore_or_one_list
by blast

```

```

corollary mixed_not_dlistset_xbefore: "dlist_independent_events a b ==>
[dlist_tempo1 a; dlist_tempo1 b] ==>
[dlist_tempo2 a; dlist_tempo2 b] ==>
[dlist_tempo3 a; dlist_tempo3 b] ==>
[dlist_tempo4 a; dlist_tempo4 b] ==>
(- Collect (dlist_xbefore a b)) =
((- Collect a) ∪ (- Collect b) ∪ Collect (dlist_xbefore b a))"

```

proof-

```

assume 0: "dlist_independent_events a b" "dlist_tempo1 a" "dlist_tempo1 b"
"dlist_tempo2 a" "dlist_tempo2 b" "dlist_tempo3 a" "dlist_tempo3 b"
"dlist_tempo4 a" "dlist_tempo4 b"
have "((- Collect a) ∪ (- Collect b) ∪ Collect (dlist_xbefore b a)) =
((Collect (λzs. ¬ a zs ∨ ¬ b zs)) ∪ Collect (dlist_xbefore b a))"
by blast
also have "... = (Collect (λzs. ¬ a zs ∨ ¬ b zs ∨ dlist_xbefore b a zs))"
by blast
hence "Collect (λzs. (¬ a zs) ∨ (¬ b zs) ∨ (dlist_xbefore b a zs)) =
((- Collect a) ∪ (- Collect b) ∪ Collect (dlist_xbefore b a))"
"Collect (λzs. ¬ (dlist_xbefore a b zs)) =
- Collect (dlist_xbefore a b)"
by blast+
thus ?thesis using 0 mixed_not_dlist_xbefore by blast
qed

```

theorem not_1_dlist_xbefore:

```

"[] dlist_tempo1 a; dlist_tempo2 b] ==>
dlist_xbefore (λxs. ¬ a xs) b zs = b zs"
by (metis Dlist_list_of_dlist dlist_tempo1_no_gap dlist_xbefore_def dlist_xbefore_implies_drop_0 slice_left_drop slice_right_take take_0)

```

corollary not_1_dlistset_xbefore:

```

"[] dlist_tempo1 a; dlist_tempo2 b] ==>
Collect (dlist_xbefore (λxs. ¬ a xs) b) = Collect b"
using not_1_dlist_xbefore by blast

```

theorem *not_2_dlist_xbefore*:

" $\llbracket \text{dlist_tempo1 } b; \text{dlist_tempo2 } a \rrbracket \implies \text{dlist_xbefore } a (\lambda xs. \neg b xs) \text{ zs} = a \text{ zs}$ "
 by (metis Dlist.empty_def append_Nil2 dlist_tempo_1_no_gap
 dlist_xbefore_append dlist_xbefore_implies_member1 drop_0 inf.commute
 inf_bot_left list.set(1) list_of_dlist_empty slice_left_drop
 slice_right_take take_0)

corollary *not_2_dlistset_xbefore*:

" $\llbracket \text{dlist_tempo1 } b; \text{dlist_tempo2 } a \rrbracket \implies \text{Collect } (\text{dlist_xbefore } a (\lambda xs. \neg b xs)) = \text{Collect } a$ "
 using *not_2_dlist_xbefore* by blast

lemma *empty_dlist_implies_false[simp]*:

" $\llbracket \text{dlist_tempo1 } a; \text{dlist_tempo2 } a \rrbracket \implies a (\text{Dlist } []) \implies \text{False}$ "
 unfolding dlist_tempo1_def dlist_tempo2_def dlist_tempo3_def dlist_tempo4_def
 slice_left_def slice_right_def size_dlist_def slice_dlist_def
 by (metis Dlist.empty_def list.size(3) list_of_dlist_empty nat_le_linear)

lemma *dlist_inf_xbefore_trans*:

" $\llbracket \text{dlist_tempo1 } b; \text{dlist_tempo3 } b \rrbracket \implies ((\text{dlist_xbefore } a b \text{ zs}) \wedge (\text{dlist_xbefore } b c \text{ zs})) \longleftrightarrow$
 $(\text{dlist_xbefore } (\text{dlist_xbefore } a b) c \text{ zs})$ "

proof-

assume 0: "*dlist_tempo1 b*" "*dlist_tempo3 b*"
 hence 1: " $\exists i. (\exists j. a (zs \dot{+} ..i) \wedge b (zs \dot{+} i..) \wedge b (zs \dot{+} ..j) \wedge c (zs \dot{+} j..)) \longleftrightarrow$
 $a (zs \dot{+} ..i) \wedge b (zs \dot{+} i..j) \wedge c (zs \dot{+} j..))$ "
 by (metis slice_left_def slice_right_def)
 have 2: " $(\exists x y. a (zs \dot{+} ..x) \wedge b (zs \dot{+} x..) \wedge b (zs \dot{+} ..y) \wedge c (zs \dot{+} y..)) \longleftrightarrow$
 $(\exists x y. a (zs \dot{+} ..x) \wedge b (zs \dot{+} x..y) \wedge c (zs \dot{+} y..))$ "
 using 0
 by (metis (no_types, hide_lams) diff_zero dlist_empty_slice dlist_tempo1_le_uniqueness
 dlist_tempo3_def dlist_tempo_1_no_gap drop_0 list_of_dlist_empty list_of_dlist.simps(3)
 max_OL not_le slice_left_drop slice_right_def take_0)
 have 3: " $((\exists i. a (zs \dot{+} ..i) \wedge b (zs \dot{+} i..)) \wedge (\exists j. b (zs \dot{+} ..j) \wedge c (zs \dot{+} j..))) \longleftrightarrow$
 $(\exists i j. a (zs \dot{+} ..i) \wedge b (zs \dot{+} i..) \wedge b (zs \dot{+} ..j) \wedge c (zs \dot{+} j..))$ "
 $"(\exists i. (\exists j. a (zs \dot{+} ..\min i j) \wedge b (zs \dot{+} j..i)) \wedge c (zs \dot{+} i..)) \longleftrightarrow$
 $(\exists i j. a (zs \dot{+} ..\min i j) \wedge b (zs \dot{+} j..i) \wedge c (zs \dot{+} i..))$ "
 by auto
 have 4: " $(\exists x y. a (zs \dot{+} ..\min x y) \wedge b (zs \dot{+} x..y) \wedge c (zs \dot{+} y..)) \longleftrightarrow$
 $(\exists x y. a (zs \dot{+} ..x) \wedge b (zs \dot{+} x..y) \wedge c (zs \dot{+} y..))$ "

```

using 0
by (metis (no_types, lifting) Dlist.empty_def append_Nil2 dlist_empty_slice
dlist_tempo_1_no_gap_append list_of_dlist_empty min.cobounded1 min_def)
have "(∃ i j. a (zs†..i) ∧ b (zs†i..j) ∧ c (zs†j..)) ↔
      (∃ i j. a (zs†..min i j) ∧ b (zs†i..j) ∧ c (zs†j..))"
using 4 by simp
hence "(∃ i j. a (zs†..i) ∧ b (zs†i..) ∧ b (zs†..j) ∧ c (zs†j..)) ↔
      (∃ i j. a (zs†..min i j) ∧ b (zs†i..j) ∧ c (zs†j..))"
using 0 2 by simp
hence "((∃ i. a (zs†..i) ∧ b (zs†i..)) ∧ (∃ j. b (zs†..j) ∧ c (zs†j..))) ↔
      (∃ i j. a (zs†..min i j) ∧ b (zs†i..j) ∧ c (zs†j..))"
using 0 3 by simp
hence "((∃ i. a (zs†..i) ∧ b (zs†i..)) ∧ (∃ j. b (zs†..j) ∧ c (zs†j..))) ↔
      (∃ j. (∃ i. a (zs†..min i j) ∧ b (zs†i..j)) ∧ c (zs†j..))"
using 3 by auto
hence "(dlist_xbefore a b zs ∧ dlist_xbefore b c zs) ↔
      (∃ j. (∃ i. a (zs†..min i j) ∧ b (zs†i..j)) ∧ c (zs†j..))"
using dlist_xbefore_def by auto
hence "(dlist_xbefore a b zs ∧ dlist_xbefore b c zs) ↔
      (∃ j. (∃ i. a ((zs†..j)†..i) ∧ b ((zs†..j)†i..)) ∧ c (zs†j..))"
by (simp add: min.commute slice_right_slice_left_absorb slice_right_slice_right_absorb)
thus ?thesis unfolding dlist_xbefore_def by simp
qed

lemma dlistset_inf_xbefore_trans:
  "⟦ dlist_tempo1 b; dlist_tempo3 b ⟧ ⟹ (Collect (dlist_xbefore a b) ∩ Collect
(dlist_xbefore b c)) =
  Collect (dlist_xbefore (dlist_xbefore a b) c)"
using dlist_inf_xbefore_trans
using Collect_cong Collect_conj_eq by blast

```

A.4.3 Formulas as ATF

In the following we prove that a formula is a valid type instantiation for all ATF classes.

A.4.3.1 Basic properties of ATF

```

instantiation formula :: (type) temporal_faults_algebra_basic
begin

```

definition

```
"neutral = Abs_formula { dlist_of_list [] }"
```

definition

```
"xbefore a b = Abs_formula { zs .
dlist_xbefore (λxs. xs ∈ Rep_formula a) (λys. ys ∈ Rep_formula b) zs }"
```

definition

```
"tempo1 a = dlist_tempo1 (λxs. xs ∈ Rep_formula a)"
```

lemma *Rep_formula_xbefore_to_dlist_xbefore*:

```
"Rep_formula (xbefore a b) =
Collect (dlist_xbefore (λx. x ∈ Rep_formula a) (λy. y ∈ Rep_formula b))"
```

unfolding *dlist_xbefore_def* *xbefore_formula_def*

by (*simp add: Abs_formula_inverse*)

lemma *Rep_formula_xbefore_bot_1*: "Rep_formula (xbefore bot a) =

```
Rep_formula bot"
```

unfolding *xbefore_formula_def*

by (*simp add: Abs_formula_inverse dlist_xbefore_bot_1*)

lemma *Rep_formula_xbefore_bot_2*: "Rep_formula (xbefore a bot) =

```
Rep_formula bot"
```

unfolding *xbefore_formula_def*

by (*simp add: Abs_formula_inverse dlist_xbefore_bot_2*)

lemma *Rep_formula_xbefore_neutral_1*: "tempo1 a ==> Rep_formula (xbefore neutral a) = Rep_formula a"

unfolding *xbefore_formula_def* *neutral_formula_def* *tempo1_formula_def*

apply (*simp add: Abs_formula_inverse*)

using *dlistset_xbefore_neutral_1* **by** *auto*

lemma *Rep_formula_xbefore_neutral_2*: "tempo1 a ==> Rep_formula (xbefore a neutral) = Rep_formula a"

unfolding *xbefore_formula_def* *neutral_formula_def* *tempo1_formula_def*

apply (*simp add: Abs_formula_inverse*)

using *dlistset_xbefore_neutral_2* **by** *auto*

lemma *Rep_formula_xbefore_not_idempotent*:

```
"tempo1 a ==> Rep_formula (xbefore a a) = Rep_formula bot"
```

unfolding *xbefore_formula_def* *tempo1_formula_def*

```

by (simp add: Abs_formula_inverse dlist_xbefore_idem)

lemma Rep_formula_xbefore_not_sym:
  "[] tempo1 a; tempo1 b] ==>
   Rep_formula (xbefore a b) ⊆ Rep_formula (-xbefore b a)"
unfolding xbefore_formula_def tempo1_formula_def uminus_formula_def
by (simp add: Abs_formula_inverse
  dlistset_xbefore_implies_not_sym_dlistset_xbefore)

```

instance proof

```

fix a::'a formula
show "xbefore bot a = bot"
unfolding eq_formula_iff Rep_formula_xbefore_bot_1 by auto
next
fix a::'a formula
show "xbefore a bot = bot"
unfolding eq_formula_iff Rep_formula_xbefore_bot_2 by auto
next
fix a::'a formula
assume "tempo1 a"
thus "xbefore neutral a = a"
unfolding eq_formula_iff
using Rep_formula_xbefore_neutral_1 by auto
next
fix a::'a formula
assume "tempo1 a"
thus "xbefore a neutral = a"
unfolding eq_formula_iff
using Rep_formula_xbefore_neutral_2 by auto
next
fix a::'a formula
assume "tempo1 a"
thus "xbefore a a = bot"
unfolding eq_formula_iff
using Rep_formula_xbefore_not_idempotent by auto
next
fix a::'a formula and b::'a formula
assume "tempo1 a" "tempo1 b"
thus "xbefore a b ≤ - xbefore b a"
unfolding eq_formula_iff less_eq_formula_def
using Rep_formula_xbefore_not_sym by simp
fix a::'a formula and b::'a formula"

```

```

assume "tempo1 a" "tempo1 b"
thus "tempo1 (inf a b)"
unfolding tempo1_formula_def
by (simp add: dlist_tempo1_inf Rep_formula_inf)
qed

```

The above proof shows basic laws about **ATF**, as shown in Eqs. (4.22a), (4.24a) to (4.24d) and (4.24g).

end

A.4.3.2 Associativity of **ATF**

```

instantiation formula :: (type) temporal_faults_algebra_assoc
begin

```

instance proof

```

fix a::"a formula" and b::"a formula" and c::"a formula"
assume "tempo1 a" "tempo1 b" "tempo1 c"
thus "xbefore (xbefore a b) c = xbefore a (xbefore b c)"
unfolding xbefore_formula_def tempo1_formula_def
by (simp add: Abs_formula_inverse dlist_xbefore_assoc)
qed

```

The above proof shows associativity law about **ATF**, as shown in Eq. (4.24h).

end

A.4.3.3 Equivalences in **ATF**

```

instantiation formula :: (type) temporal_faults_algebra_equivs
begin

```

definition

```

"independent_events a b =
dlist_independent_events
(λxs. xs ∈ Rep_formula a) (λxs. xs ∈ Rep_formula b)"

```

definition

```

"tempo2 a = dlist_tempo2 (λxs. xs ∈ Rep_formula a)"

```

definition

```

"tempo3 a = dlist_tempo3 (λxs. xs ∈ Rep_formula a)"

```

definition

```

"tempo4 a = dlist_tempo4 (λxs. xs ∈ Rep_formula a)"

instance proof
  fix a::"a formula" and b::"a formula"
  assume "tempo1 a" "tempo1 b"
  thus "inf (xbefore a b) (xbefore b a) = bot"
    unfolding xbefore_formula_def tempo1_formula_def bot_formula_def
    inf_formula_def
    by (simp add: dlistset_xbefore_and Abs_formula_inverse)
  next
  fix a::"a formula" and b::"a formula"
  assume "independent_events a b" "tempo1 a" "tempo1 b" "tempo2 a" "tempo2 b"
         "tempo3 a" "tempo3 b" "tempo4 a" "tempo4 b"
  thus "sup (xbefore a b) (xbefore b a) = inf a b"
    unfolding xbefore_formula_def tempo1_formula_def tempo2_formula_def
    tempo3_formula_def tempo4_formula_def independent_events_formula_def
    sup_formula_def inf_formula_def
    by (simp add: dlistset_xbefore_or Abs_formula_inverse)
  next
  fix a::"a formula" and b::"a formula"
  assume "tempo2 a" "tempo2 b"
  thus "tempo2 (sup a b)"
    unfolding tempo2_formula_def
    by (simp add: dlist_tempo2_sup Rep_formula_sup)
  next
  fix a::"a formula" and b::"a formula"
  assume "tempo3 a" "tempo3 b"
  thus "tempo3 (inf a b)"
    unfolding tempo3_formula_def
    by (simp add: dlist_tempo3_inf Rep_formula_inf)
  next
  fix a::"a formula" and b::"a formula"
  assume "tempo4 a" "tempo4 b"
  thus "tempo4 (sup a b)"
    unfolding tempo4_formula_def
    by (simp add: dlist_tempo4_sup Rep_formula_sup)
qed

```

The above proof shows equivalences in ATF, as shown in Eqs. (4.22b) to (4.22d), (4.25a) and (4.25b).

end

A.4.3.4 Transitivity in ATF

```

instantiation formula :: (type) temporal_faults_algebra_trans
begin
instance proof
fix a::"a formula" and b::"a formula" and c::"a formula"
assume "tempo1 a" "tempo1 b" "tempo1 c" "tempo2 a" "tempo2 b" "tempo2 c"
thus "inf (xbefore a b) (xbefore b c) ≤ xbefore a c"
unfolding tempo1_formula_def tempo2_formula_def xbefore_formula_def
less_eq_formula_def inf_formula_def
by (simp add: dlistset_xbefore_trans Abs_formula_inverse)
next
fix a::"a formula" and b::"a formula" and c::"a formula"
assume "tempo1 b" "tempo3 b"
thus "inf (xbefore a b) (xbefore b c) = xbefore (xbefore a b) c"
unfolding xbefore_formula_def inf_formula_def tempo1_formula_def
tempo3_formula_def
by (simp add: Abs_formula_inverse dlistset_inf_xbefore_trans)
qed

```

The above proof shows transitivity in ATF, as shown in Eq. (4.27f).

end

A.4.3.5 Mixed operators in ATF

```

instantiation formula :: (type) temporal_faults_algebra_mixed_ops
begin
instance proof
fix a::"a formula" and b::"a formula" and c::"a formula"
show "xbefore (sup a b) c = sup (xbefore a c) (xbefore b c)"
unfolding xbefore_formula_def sup_formula_def
by (simp add: mixed_dlistset_xbefore_or1 Abs_formula_inverse)
next
fix a::"a formula" and b::"a formula" and c::"a formula"
show "xbefore a (sup b c) = sup (xbefore a b) (xbefore a c)"
unfolding xbefore_formula_def sup_formula_def
by (simp add: mixed_dlistset_xbefore_or2 Abs_formula_inverse)
next
fix a::"a formula" and b::"a formula"
assume "independent_events a b" "tempo1 a" "tempo1 b" "tempo2 a" "tempo2 b"
"tempo3 a" "tempo3 b" "tempo4 a" "tempo4 b"
thus "(- xbefore a b) = (sup (sup (- a) (- b)) (xbefore b a))"
by (simp add: Abs_formula_inverse xbefore_formula_def uminus_formula_def)

```

```

sup_formula_def independent_events_formula_def tempo1_formula_def
tempo2_formula_def tempo3_formula_def tempo4_formula_def
mixed_not_dlistset_xbefore)

next
fix a::"a formula" and b::"a formula" and c::"a formula"
assume "tempo2 a"
thus "inf a (xbefore b c) =
      sup (xbefore (inf a b) c) (xbefore b (inf a c))"
apply (auto simp add: xbefore_formula_def sup_formula_def inf_formula_def
      tempo2_formula_def Abs_formula_inverse)
using and_dlistset_xbefore_equiv_or_dlistset_xbefore Abs_formula_inverse
by fastforce
next
fix a::"a formula" and b::"a formula"
assume "tempo1 a" "tempo2 b"
thus "xbefore (- a) b = b"
unfolding xbefore_formula_def tempo1_formula_def tempo2_formula_def
uminus_formula_def
by (auto simp add: Abs_formula_inverse not_1_dlistset_xbefore
      Rep_formula_inverse)
next
fix a::"a formula" and b::"a formula"
assume "tempo1 b" "tempo2 a"
thus "xbefore a (- b) = a"
unfolding xbefore_formula_def tempo1_formula_def tempo2_formula_def
uminus_formula_def
by (auto simp add: Abs_formula_inverse not_2_dlistset_xbefore
      Rep_formula_inverse)
qed

```

The above proof shows laws with mixed Boolean and **XBefore** operators, as shown in Eqs. (4.27a), (4.27b), (4.27e) and (4.29a) to (4.29c).

end

A.4.4 Equivalence of the new definition of **XBefore** with the old one

```

definition old_dlist_xbefore
where
"old_dlist_xbefore S T zs ≡
  (∃ xs ys. S xs ∧ ¬ T xs ∧ T ys ∧ ¬ S ys ∧
    set (list_of_dlist xs) ∩ set (list_of_dlist ys) = {} ∧
    list_of_dlist zs = (list_of_dlist xs) @ (list_of_dlist ys))"

```

```

theorem old_dlist_xbefore_equals_new_xbefore:
  "[] dlist_tempo1 S; dlist_tempo1 T ] ==>
   dlist_xbefore S T zs = old_dlist_xbefore S T zs"
unfolding dlist_xbefore_append old_dlist_xbefore_def
using dlist_tempo_1_no_gap_append
by blast

```

A.4.5 Soundness and completeness on the mapping rules

```

theorem temporal_faults_algebra_mapping_soundness:
  "\forall (f1::'a formula) (f2::'a formula). \exists S. ((Rep_formula f1 = S \wedge Rep_formula
f2 = S) \longleftrightarrow f1 = f2)"
by blast

```

```

theorem temporal_faults_algebra_mapping_completeness:
  "\forall (S::'a dlist set). \exists f::'a formula. Rep_formula f = S"
using Abs_formula_inverse by auto

```

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