Technische Universität Kaiserslautern

Safety and Reliability of Embedded Systems

(Sicherheit und Zuverlässigkeit eingebetteter Systeme)

Fault Tree Analysis
Obscurities and Open Issues

Technische Universität Kaiserslautern

Content

What are Events?

- In probability theory, everything that is true with a certain probability is called “event”
- In software / systems engineering (and in common language), an event is something occurring at a given point in time
- In FTA, events can be
  - Sudden events ("Bolt breaks")
  - States or conditions ("Valve is blocked")
  - (Informal) propositions ("Fire is not detected by supervisor")

☝ **All of them may be useful, but specify clearly what you mean**

- Note the differences regarding probabilities
  - States / propositions have a probability (at a given time)
  - Events have a probability density or rate
- (Out-dated) DIN 25424 features appropriate formulas for probability and probability density

Examples for Problematic Event Semantics

Priority AND: Output event occurs when all input events occur in a specific order

- If FT events are sudden events: When does output event occur?
  - E.g. simultaneously to the last of the input events
- If output event is a logical proposition: The proposition is true (all the time!), if the input events do occur in the right order
  - But can input events also be propositions then? How can then Input 1 occur before Input 2?
- If FT events are states / conditions / predicates that can be true or false at given times
  - Input 1 can become true before Input 2
  - Output condition is true upon the time when the last input condition is true

Inhibit, Enabler / Conditioning Events

Inhibit: Output event occurs when input event occurs and inhibit event is not true

- ☐ Inhibit event has state / condition semantics
- ☐ Sometimes enabler events (states) are distinguished from initiator events (trigger semantics)
- ☐ Separate symbols are available

Basic Event / Initiator

Conditioning Event / Enabler

The Use of NOT

MCS based probability calculation is not suitable for negated events!

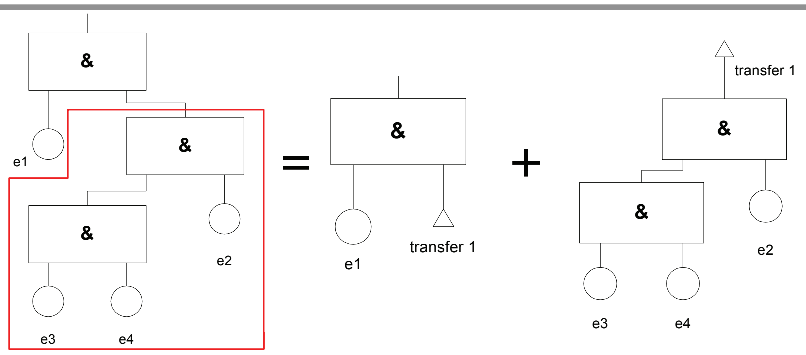
- ☐ A FT without NOT is called "coherent"
  - "A system can never get better if more components fail"
- ☐ Some NOTs are virtual (e.g. in transcriptions of voter, XOR, ...)
- ☐ If FT events are sudden events
  - How can their occurrence be negated?
  - In this case, NOT makes no sense
- ☐ If FT events are states / conditions / predicates / logical propositions
  - Negation makes sense
  - BDD algorithm can handle negated variables
  - Minimal cut sets → Prime implicants (may contain negated events)

cf. John Andrews: “To Not or not to Not”

Generalization vs. Causation Gates

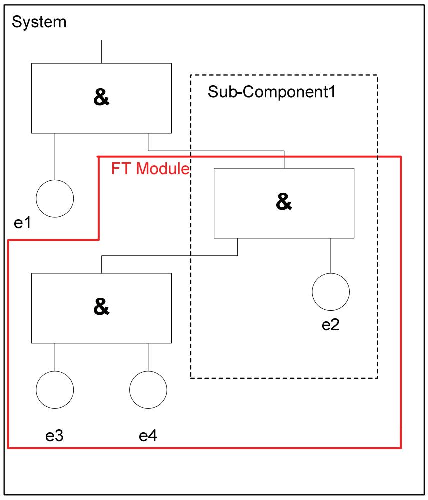
- Sometimes gates suggest causality
  - Electrical short circuit OR defective gas tube ⇒ fire
- Sometimes gates suggest generalization / decomposition
  - Engine defective OR tire defective = car defective
- In original FT standards no distinction, some researchers do distinction
  - Sometimes, two pairs of AND / OR are proposed [Gorski]
  - Some say that AND means causation and OR means decomposition [FT Handbook]
- Whether or not FTs express causality at all can be discussed...

Issues about Decomposition



- FTs are hierarchical by nature
- Traditionally, FTs are decomposed by modules (independent sub-trees)
- Each module is replaced by a single event with the same probability
- Each module can be analyzed independently
- Alternatively, partitioning into pages by transfer symbols

FT Decomposition by Modules



Modules are <u>independent</u> sub-trees

But:

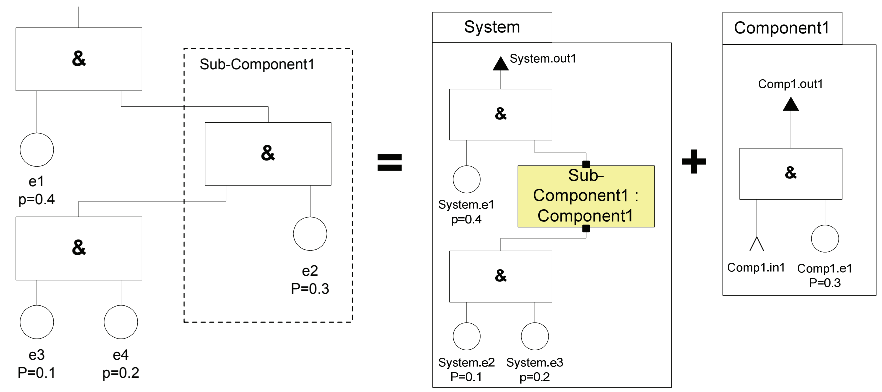
Technical components often influence each other

Technical components are not always modules!

Deficiencies of Classical Module Concept

- Module borders may be orthogonal to component borders
- Attachment of (partial) fault trees to components is not possible if components have external influences
- Division of labor (e.g. supplier/integrator) is not possible
- Modeling of some component by other models than fault trees is not possible
- Partitioning of fault trees into pages (using transfer ports) is a solution to some degree, but still no division of labor or reuse

Recent Approach: Component Fault Trees



Here, "component" means technical unit.
Components are connected by ports like in architectural models.
New paradigm: Components represent Boolean formulas

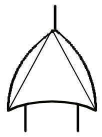
Temporal Functions

- Events can be understood as propositions that are true or false at each given point of time
- Supplying time functions instead of constant probabilities allows to plot reliability/availability function for the complete system
  - Events can be exponentially distributed, Weibull distributed etc.
  - Useful in combination with Markov analysis
  - Mission time for each event or sub-component specifies time
- Important special case: Exponential distribution
  - $P(t) = 1- e^{-\lambda t}$, λ: Failure rate; P: Probability, that component has failed
  - OR leads to an exponential function as gate output, but AND does not!

Attention when representing events by their occurrence rate:
Output function is not always exponential!

Temporal Relations between Events

- ☐ Standard FTA is based on Boolean logic and cannot handle temporal sequences
- ☐ Priority AND expresses probability that event 1 occurs before event 2
  - Only useful if time functions (and not static probabilities) are used
  - Probability of system failure before t is probability that E1 occurs before some intermediate point of time and E2 occurs after that point, accumulated for all points of time between 0 and t



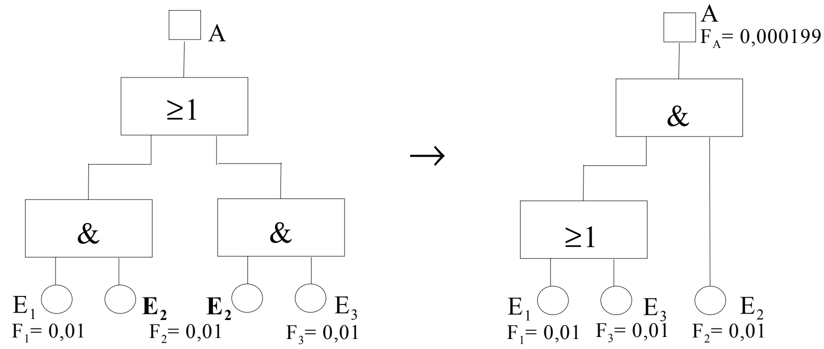
E1 E2

$$P_{failed}(t) = \int_0^t f_2(t_2)\left(\int_0^{t_2} f_1(t_1)\,dt_1\right)dt_2$$

Dependencies

- ☐ Stochastic independence is an important assumption for combinatorial approaches
- ☐ Repeated events as special case of dependency can be handled by restructuring the Boolean formula
- ☐ For special cases (e.g. spares), there are solutions
- ☐ When probabilities are small, errors may be negligible if dependencies are not taken into account
- ☐ Correct calculation in presence of arbitrary dependency is only possible by state-based models
- ☐ Functional dependency gate in DFT allows to express secondary faults

Elimination of Repeated Events



- By restructuring the Boolean formula, repeated events can be avoided

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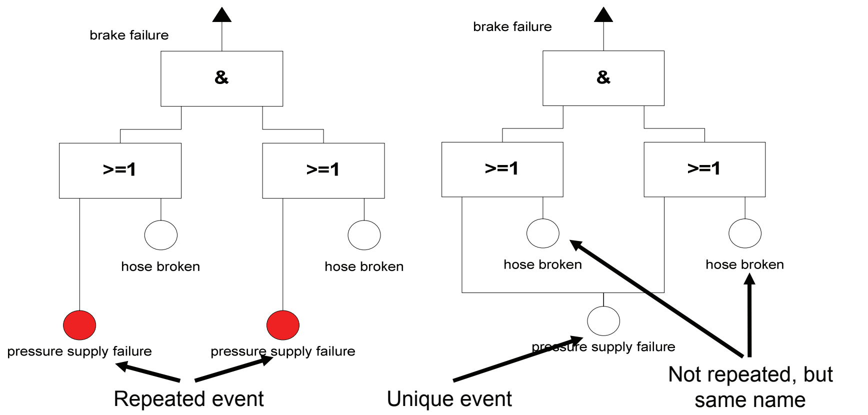
Repeated Events: Tree vs. DAG



- Directed Acyclic Graphs (instead of trees) eliminate repeated events
- A namespace concept is desirable (implemented in Component Fault Trees)

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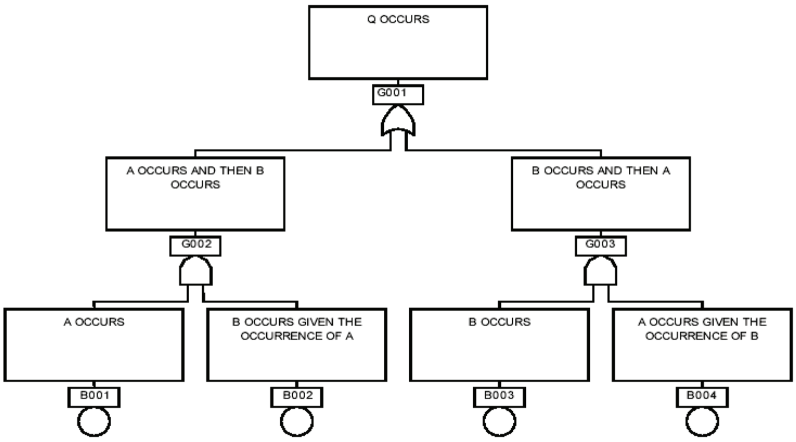
Spares and Spare Pools

- ☐ A special case of dependency is the usage of spares
- ☐ System fails if primary unit fails and spare also fails or has already failed before
- ☐ While the primary unit is operating, spares fail
  - not at all → cold spare
  - at a reduced rate (specified by a factor) → warm spare
  - at the normal rate (hot spare)
- ☐ Special spare gates have been proposed
- ☐ Spare pool: Not only one spare unit, but n spare units with identical failure rate

Explicit Dependencies



Other ways to deal with dependencies

- ☐ Functional Dependency Gate (in some packages)
  - Output event occurs necessarily if input occurs
  - Output event can also occur spontaneously

☝ **Many attempts have been made to bring special cases of dependency into FTA. At a certain point, state-based models (e.g. Markov chains) are a better fit (but analysis is usually much slower!)**

Integration with other models

- ☐ Fault trees can and should be integrated with
  - Markov chains: to describe basic events in presence of dependencies
  - Event trees: to describe consequences of the top-event
- ☐ Fault trees can and should be used in conjunction with
  - FMEA
  - other hazard analysis models (Preliminary Hazard Analysis, Common Cause Analysis, ...)
  - general systems and software modeling techniques

☝ **Formal integration with software / systems modeling is desirable, but not yet achieved to a satisfactory degree**

FTA for Software

- ☐ FTA stems from an era when (at least) safety critical systems were purely electrical / mechanical
- ☐ They have "working/failed" semantics
- ☐ They cannot natively capture the dynamic nature of software
- ☐ There have been several attempts to apply FTA to software or to derive FTs from software
  - partly based on source code statements
  - partly based on statecharts or formal methods

☝ **Applying FTA to software controlled systems is still an issue**

Is there a formal semantics for FTA?

- ☐ FTs are intuitive, but unclear semantics is an issue when
  - constructing FTs automatically
  - integrating FTs with other kinds of models
  - using dynamic extensions
- ☐ Some recent research work about formalizing FTA
  - formalizing the meaning of gates
  - proving that FT is complete and consistent
- ☐ Different formalisms used
  - Z (algebraic specification)
  - Interval Temporal Logic, Duration Calculus (temporal/real time logic)
  - Translation into Markov chains and different kinds of probabilistic Petri nets

**Formalization is not agreed upon.
Different researchers use different approaches**

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